1973-03

Development and application of an analog scheme for predicting the intensification of Western North Pacific tropical cyclones

Foster, Kent William

Monterey, California : Naval Postgraduate School

http://hdl.handle.net/10945/16562

DEVELOPMENT AND APPLICATION OF AN ANALOG SCHEME FOR PREDICTING THE INTENSIFICATION OF WESTERN NORTH PACIFIC TROPICAL CYCLONES

Kent William Foster

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

DEVELOPMENT AND APPLICATION OF AN ANALOG SCHEME FOR PREDICTING THE INTENSIFICATION OF WESTERN NORTH PACIFIC TROPICAL CYCLONES

by

Kent William Foster

Thesis Advisor: R. J. Renard

March 1973

Approved for public release; distribution unlimited.

Development and Application of an Analog
Scheme for Predicting the Intensification
of
Western North Pacific Tropical Cyclones

by

Kent William Foster
Lieutenant, United States Navy
B.S., New York State College of Forestry, 1967

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY

from the

NAVAL POSTGRADUATE SCHOOL
March 1973

ABSTRACT

Various meteorological parameters were examined to determine their predictive value for forecasting intensity changes of Western North Pacific tropical cyclones using an analog forecast scheme. A number of procedures were devised to quantitatively define the forecast potentials of these parameters in a systematic method. Based on the results of these procedures, predictors for the 24-hour, 48-hour, and 72-hour forecast periods were defined.

To evaluate the skill of the predictors and the procedures used to define them, an analog intensification forecast scheme was developed and applied to a number of test cyclones. The results of these forecasts were compared to the acceptability criteria established by the Joint Typhoon Warning Center, Guam and to official forecasts issued by this activity.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENT

The author wishes to express his sincere appreciation to Dr. Robert J. Renard, faculty advisor, for his professional advice and guidance, and for his personal support throughout the duration of this study.

Appreciation is also extended to CDR. Jerry D. Jarrell, USN, for his valuable assistance in many aspects of the research. Special thanks also go to Samson Brand, Environmental Prediction Research Facility, Monterey, California, for his useful recommendations in initiating the study, and to Dr. Russell Elsberry for his careful review of the manuscript.

I. INTRODUCTION

A. BACKGROUND

Prior to the mid-1960s, studies in the field of tropical meteorology progressed at a very slow pace. A literature search through various meteorological journals published before 1965 reveals a strikingly small number of articles and reports pertaining to tropical meteorology. However, since that time, the amount of research in progress and the knowledge of the tropical ocean-air regime have increased by orders of magnitude. Two factors have been primarily responsible for the increased efforts and results: the meteorological satellite and the development of the efficient, large capacity, second generation digital computer. Garstang [1] states "...the advent of the meteorological satellite, and the power of the computer have collectively led to great effort and considerable progress in the realm of tropical meteorology...".

The one phenomenon of tropical meteorology that has been the object of more research than any other is the tropical cyclone--the hurricane or typhoon. The high winds, large storm surges, and excessive amounts of rainfall associated with these systems pose a highly destructive threat to many densely populated areas of the world, as well as to many high density shipping routes and areas of extensive naval operations. Even though tropical cyclones lose their

organized circulation rapidly as they encounter large land masses, the unstable remnants of these systems can cause wide-spread damage far inland. Their far-ranging destructive nature has been the impetus for extensive research on the natural forces which initiate and maintain tropical cyclones.

Much of the research associated with tropical cyclones has been directed at improving the accuracy and timeliness of tropical cyclone forecasts. The major factors associated with the forecasting are the initial development, movement and intensification. With the utilization of high speed computers, many objective movement forecast schemes have been developed and are in operational use as forecast aids. For example, there are currently six computerized objective forecast aids for typhoon movement in use at Fleet Weather Central/Joint Typhoon Warning Center Guam (JTWC)[2]. None of these objective schemes are considered as an adequate forecast technique, but are used as aids and are component of the final product, the official forecast. However, there are currently no computerized objective schemes in operational use as aids to forecasting tropical cyclone intensification. The bulk of all forecast research efforts has been directed at movement, for if the movement cannot be predicted adequately, then even a perfect intensity forecast may have limited value. The overwhelming emphasis placed on movement rather than intensity forecasts is documented by

the fact that verification of the latter was not attempted at JTWC prior to 1969. But with the increasing accuracy of movement forecasts that has been experienced in recent years, the intensity forecast is becoming more relevant [3].

Due to the lack of objective aids for forecasting tropical cyclone intensification, the forecaster is forced to rely on the limited amount of current and recent past data at hand to arrive at a forecast. At JTWC the basic forecast procedure in use is a linear extrapolation of past intensity changes, subjectively modified by expected conditions along the forecasted track and by climatology [2]. These procedures are limited in that, for newly developed systems, extrapolation is especially unreliable (if at all possible) and rapid deepening cannot be forecast to an adequate degree of accuracy. An objective scheme for use as an intensification forecast aid would be a valuable asset to the tropical forecaster.

One of the objective aids for typhoon movement employed at JTWC is an analog scheme called TYFOON. Forecasts are provided in the form of probability ellipses of future position,derived from the movement of a number of reports of past cyclones that have been screened, selected as analogs, and weighted on the basis of their similarity to the subject current cyclone. The degree of analog similarity is a function of time of occurrence (month and day), geographic position, and a number of meteorological parameters, hereafter

called analog elements. The numerical values associated with the elements of a particular analog are compared to the respective analog elements of the current cyclone to determine their resemblance. The degree of resemblance is used to assign a weight to the respective analog which will define its importance to the final results. A full description of the original development of TYFOON is given in [4]. The overall results of TYFOON have been the best of any objective scheme in use at JTWC [2]. The lack of objective forecast intensification aids and the success of the TYFOON analog scheme for movement were the prime stimulants for initiating this study.

B. OBJECTIVES OF THE STUDY

The development of the TYFOON forecasting aid necessitated the selection of various parameters to describe the time, position, and synoptic features of current and past tropical cyclones in the western North Pacific Ocean. The historical data were assembled and compiled into a digital format for computer utilization. The primary objective of this study was to conduct a pilot study of the analog parameters associated with TYFOON to determine their potential as predictors of tropical-cyclone intensification. With the assumption that some positive results would become apparent from the primary objective, the secondary objective was to devise a forecast scheme that would test the predictive

value of the analog data and serve as a first attempt at providing the forecaster with an objective analog forecasting aid to predict tropical-cyclone intensification.

C. AREA OF STUDY

The area of study was restricted to the region for which the necessary tailored data have been assimilated and digitized for use by TYFOON. This area consists solely of the western North Pacific Ocean. Specifically, it is that region of the Pacific north of the equator and west of 180 degrees. This area experiences more than twice the number of tropical cyclone occurrences in comparison with any other area and, further, is the only region where the systems appear in all 12 months of the year [5]. Consequently, the area is more suited to analog forecasting than any other area of tropical cyclone occurrence due to the availability of large amounts of tropical cyclone data.

D. DATA

1. General

The data available for the study were dictated by that information which has been compiled for use by TYFOON. It consists of various parameters of two major categories: cyclone identity elements and analog identity elements. These parameters are listed in Appendix A. The data have been collected and digitized for each six-hourly report of every known tropical cyclone (depression, storm, or typhoon) since 1945, and at the time of this study, such data were

available through 1969. The information includes best-track data, a result of post-season analysis of operational data. The originally observed and analyzed data have been re-analyzed to insure consistency in development and movement to a degree that may not have been possible at the time of collection.

Only limited information was available on the errors inherent in the data. Many of the parameters were assigned numerical values as a result of subjective analysis, and therefore, it was very difficult to specify the expected errors in these data. It is believed that the maximum sustained surface wind has an error of 10 to 15 percent at the time of observation and warning, while that error may be reduced to 10 percent after post analysis [6]. Estimates of errors associated with other data have been provided[1] and are listed in Appendix A.

When the analog elements for use in TYFOON were selected, only cyclone movement was being considered. Therefore, the data did not include many parameters that are closely associated with typhoon intensity changes, such as thermal structure of the cyclone position of the monsoon trough, or sea-surface temperature, among others. However, there were some parameters such as the past 12-hour change in sea-level pressure, the past-movement of the cyclone, and the minimum 700-mb height above the vortex, which are

---

[1]From informal discussion with CDR. J. D. Jarrell.

known to have some relation to intensity change, at least in some situations.

2. Selection For the Study

For the purpose of this study, several test cases were selected, and for each test case a number of analog candidates were defined and compared to the test case with respect to intensification characteristics and analog element behavior. A test case was defined as one six-hourly report of a tropical cyclone. An analog candidate was defined as one six-hourly report of any tropical cyclone (other than the one from which the test case was selected) which by virtue of its position and time of occurrence (month and day), was determined to be similar to the test case.

It is a well documented fact that the rate of occurrence and the general behavior of tropical cyclones vary from season to season and month to month. As to the variations in intensification behavior, [7] and [8] provide substantial evidence. Since this study was aimed at the relationships between analog elements and intensification, it was desirable to eliminate other variables related to intensification (e.g. month of occurrence) without severely restricting the number of possible test cyclones and analog candidates. Therefore, it was decided to select for the study only those tropical cyclones occurring in one season of the year. It was also considered desirable to initiate the research using somewhat well-behaved vorticies. That

is, a season in which there occurs relatively little rapid deepening and little unsuspected weakening over the open ocean was considered most favorable for this pilot study. However, it was decided that the season selected should also contain a relatively large number of occurrences, for it has been observed that better results are obtained from the TYFOON analog scheme when larger numbers of analogs are available.[2] Again, it was felt that the most ideal, yet not overly restrictive, conditions should be studied initially.

Studies by Brand [7] indicate that August tropical cyclones would best fulfill the above requirements. They exhibit relatively little rapid deepening, while also showing little weakening over low-latitude open ocean areas. August also has the second highest frequency of occurrence[3] of tropical cyclones. Therefore, it was decided to select at least the bulk of the test cases from this month. To allow for a variable time span from which analog candidates could be selected for any August test case, it was necessary to include the tropical cyclones of July and September in the data.

Based on the above considerations, the analog data for the months of July, August and September for the years 1945 to 1969 were obtained (on magnetic tape) from the Environmental Prediction Research Facility, Monterey, California.

---

[2] From informal discussion with CDR. J. D. Jarrell.

[3] Number of six-hourly reports.

II. PROCEDURES

A. DEFINITION OF CYCLONE INTENSITY

In a study of tropical cyclone intensification, the first necessary step is to define intensity. The variables most commonly associated with the various stages of development of a tropical cyclone from depression to storm to typhoon or hurricane include the amount, orientation, and maximum height of clouds, the minimum sea-level pressure, and the maximum wind. The content of the available data eliminated the cloud conditions as the intensity parameter for this study. Of the remaining two parameters, minimum sea-level pressure was estimated to be subject to smaller observational errors than maximum wind, and thus would be a more reliable indicator of intensity. However, it is the maximum wind that is of prime interest to the forecaster and recipients of his services; therefore, it was this parameter that was selected to describe the tropical cyclone intensity.

B. SELECTION OF TEST CYCLONES

For the initial study, a total of 30 test cases were selected. The selection was not random, but was carried out in such a manner to insure that a wide range of initial intensities and positions were represented. Widely varying intensification characteristics, to include development and

weakening, were also exhibited by the test cases. As mentioned before, it was not desirable to be overly restrictive with the data as this would possibly inhibit favorable results. Based on the findings in this study, restrictions could be applied, if necessary, in subsequent studies. In other words, if one adequate objective forecast scheme could not be derived for cyclones of widely ranging initial intensities and positions, then the input data could be stratified with respect to these variables and different forecast schemes attempted for the various classes of cyclones.

Other factors were considered in the test cyclone selection. Since one avenue of research utilized historical data of the test cases, a restriction was placed on the minimum amount of history possessed by a number of the cases. There were, however, some test cases with no recorded historical data. Recurvature was also considered and a number of the test cyclones were selected on the basis of whether or not recurvature took place within the forecast periods or in the recent past.

As stated before, the bulk of the test cases were selected from the month of August. However, to insure that a sufficient number of appropriate test cases from recent years collectively represented a wide range of initial intensities and positions, and to avoid an excessive number of related test cases (from the same tropical cyclone) it was found necessary to select a few test cyclones from the

month of September. The 30 test cases initially selected for the study are listed in Appendix B.

The total number of six-hourly reports included in the three-month period of data obtained for the study amounted to over 7500. It is realized that only 30 test cases may not constitute a representative sample of all analog parameters involved. However, the full range of possible initial intensities and a highly variable distribution of initial positions were represented. It was believed that if useful persistent relationships (between the analog elements and intensification) not only exist, but also remain valid for highly variable initial conditions, then at least some indications should be observed from as few as 30 test cases. Again, it is emphasized that the prime purpose of this study was to determine _if_ some analog elements possess any potential as predictors of intensification, not to quantitatively describe the various degrees of this potential.

C. BASIC APPROACH TO THE MAIN OBJECTIVE

The main objective of this study required the development of a procedure that would examine the analog elements and identify any behavior which appeared to be related to intensification. Several trial and error forecast schemes could have been attempted using various parameters with associated weight factors being assigned intuitively. It was decided, however, that a systematic approach would be more likely to bear fruitful results.

In an analog intensification forecast scheme, a comparison would be made of known elements (predictors) of the current cyclone with those of past cyclones that occurred within specified space and time limits, as well as exhibiting an intensity within some predetermined range. Based on a comparison of the analog elements, a number of analog candidates that most closely resemble the current cyclone would be determined. The changes in intensity exhibited by these most similar analogs would be formulated into a forecast for the current cyclone.

To investigate the forecast potential of the analog elements, it was decided to use the inverse of an analog forecast procedure. For a given test case of known future intensification, all six-hourly reports of past cyclones were screened to determine those that occurred within specified time, space, and initial intensity limits. Then, rather than classify the analogs on the basis of their element values (as would be done in a forecast scheme) the future intensification of each selected analog candidate was determined, and they were classified according to their deviations in future intensification from that of the current cyclone. A class was defined as a collection of analogs that exhibited similar deviations in intensification from that of the test case for a given forecast period. Each class of analogs represented an intensification range, and the similarity of that range to the test cyclone intensification varied from class to class. The analog elements

associated with the candidates in each class were ranked to determine their average degree of matching with respect to the test case elements. This basic approach will become better understood as the various procedures are discussed.

The hypothesis around which the basic approach to the study was designed specifies that if any of the analog elements were related to intensification, then the degree of matching of these elements, with respect to the current cyclone values, should decrease as the deviation in intensification of the associated analog candidates, from that of the test case, increases. If the deviations in intensification are thought of as forecast errors, then the hypothesis implies that higher degrees of matching are associated with smaller forecast errors for potential predictors of intensification. If any of the elements exhibited this trend with some degree of consistency, then a class of analogs with intensification similar to the test case could be determined, and this intensification used as a forecast aid. This basic procedure was considered to be the most efficient and direct approach to the main objective.

The main problems encountered in this basic approach were deciding on what criteria to use for the analog classification and what technique to use for the degree of matching computation. The following sections describe the various specific procedures that were developed in an attempt to accomplish the primary and secondary objectives. All

procedures were programmed in FORTRAN IV for use with the IBM 360 computer at the Naval Postgraduate School, Monterey, California.

D. FIRST APPROACH TO THE OBJECTIVE

The first procedure developed for the study was an inverse analog program, as described in the previous section. It consisted of two basic operations: (1) test case definition and analog selection; (2) analog classification and parameter rank computation.

In the first operation a test cyclone was defined by means of a test case identification number, by its associated latitude, longitude, and month, day and time of occurrence, and by its associated analog elements. The future intensifications for 12, 24, 48, and 72 hours, exhibited by the test case, were also defined. For test cases not exhibiting a particular future intensification, a code of 999 was assigned. The intensification for each forecast period was defined as the difference between the intensit at the end of the respective period and the initial intensity.

The next step was to define the time, space, and initial intensity limits to be utilized in the analog selection. Time and space screening criteria of plus or minus 15 days from the day of the test cyclone, and plus or minus five degrees latitude and longitude from the initial position of the test case were selected for this procedure. In general,

vorticies of extremely different intensities exhibit unlike intensification characteristics over an extended period of time. For example, a young developing tropical depression would be unlikely to exhibit intensification characteristics similar to that of a fully-developed super typhoon. Under conditions favorable for development, the young cyclone could continue to intensify for a considerable length of time, whereas the super typhoon, being near or at its point of maximum intensity, would not be expected to exhibit this behavior. In an analog forecast scheme, an initial intensity screen would be utilized to eliminate unnecessary and undesirable noise in the selected analogs. Since the analog selection phase of this procedure was similar to that which would be utilized in an analog forecast scheme, the initial intensity screen was applied. Limits of plus or minus 20 knots from that of the test case were defined for the analog selection. With the test cyclone and its associated screening criteria established, the procedure continued with the analog selection.

Each six-hourly report of all past tropical cyclones (contained in the data), excluding the cyclone with which the test case was associated, was screened with respect to its time of occurrence (month and day), position, and initial intensity. All those reports satisfying the previously defined screening criteria were designated analog candidates. For each analog selected, the associated 12-, 24-, 48-, and 72-hour future intensifications were determined. With the

analogs selected and their intensifications computed, the first operation in this procedure was completed.

The analog classification and parameter rank computation proved to be the most difficult aspect of the study. No previous guidelines were available to indicate what would be the best approach. The various methods of attack were somewhat trial and error, but all were based on the hypothesis stated earlier, and all had one concept in common, namely the analogs were classified according to their deviations in intensification from that of the test case for each forecast interval.

In the first approach to the analog classification, positive and negative deviations were considered. For each forecast period the following analog classification scheme was implemented:

Class 1	Deviation =	$0 \rightarrow +9$ KTS
Class 2	Deviation =	$0 \rightarrow -9$ KTS
Class 3	Deviation =	$10 \rightarrow 19$ KTS
Class 4	Deviation =	$-10 \rightarrow -19$ KTS
.	.	.
.	.	.
.	.	.
Class 13	Deviation =	$70 \rightarrow 79$ KTS
Class 14	Deviation =	$-70 \rightarrow -79$ KTS

With all (or most) of the analog candidates classified, the next step was to compute analog element ranks. Analogs with deviations in intensification not defined above were eliminated from further investigation.

For each analog element associated with an analog candidate in the above classes, a rank was computed to determine the degree of matching with the respective test cyclone

element. In this approach the ranges of the analog elements over the entire data file were utilized.[5] The rank of the N^{th} element of each classified analog candidate was computed using the following formula:

$$R(N) = \left(1.0 - \left|\frac{PA(N) - PT(N)}{r(N)}\right|\right) 100.0 \qquad (1)$$

$PA(N)$ = N^{th} element value of the analog
$PT(N)$ = N^{th} element value of test cyclone
$r(N)$ = range of N^{th} element
$R(N)$ = rank of N^{th} element associated with the particular analog

The ratio $\left|\frac{PA(N) - PT(N)}{r(N)}\right|$ indicates how different the two values of the N^{th} element are as compared to the maximum possible difference. Subtracting this quantity from 1.0 results in a higher rank for a closer match. For an identical match, PA(N) = PT(N) and R(N) = 100.0; a rank of zero would indicate the two values, PA(N) and PT(N), were on opposite extremes of the range.

Once the elements were ranked for all classified analo s, the average rank of each element was computed for each cl: ss, thus arriving at an average degree of matching. The standard deviation of the individual ranks in each class was also calculated for each analog element. Also for each element, a graph of average rank versus class deviation in intensification was plotted. Recalling that these deviations could

---

[5]Maximum and minimum values of the analog elements and the ranges were computed in a separate program and specified in this procedure. For direction of movement elements, the range was specified as 180 degrees.

be considered forecast errors, these graphs were essentially the average degree of matching versus forecast error.

This procedure was applied to the first 15 test cyclones listed in Appendix B, and the results were analyzed. Graphs revealing a decreasing average degree of matching with increasing forecast error were not observed with any persistence for any of the analog elements. In several cases, an increasing average degree of matching with increasing forecast error resulted with the past direction and speed of movement elements. No physical interpretation could be given for this behavior.

One obvious fault in the procedure was noted. For the 48- and 72-hour forecast periods, and to a lesser extent the 24-hour period, the selected analogs in any one class exhibited markedly different intermediate intensification characteristics. In a 48-hour period, for example, one analog may have intensified 30 knots in a gradual but steady manner, while another analog may have intensified 50 knots in the first 24 hours, remained steady for 12 hours and then weakened by 20 knots in the next 12 hours. These two hypothetical cases exhibit markedly different behavior, but since each experiences a net 48-hour intensification of plus 30 knots they would be classified together under the current procedures. Since it was the intention to classify only similar analogs together in order to study the variable behavior of the analog elements, modified definitions of

intensification were implemented for the 24-, 48-, and 72-hour forecast periods, and are shown below. The letter I represents intensity and the subscripts indicate the number of hours from the time of occurrence of the test cyclone or analog.

$$\begin{aligned} \Delta I_{24} &= I_{24} - I_{12} \\ \Delta I_{48} &= I_{48} - I_{24} \\ \Delta I_{72} &= I_{72} - I_{48} \end{aligned} \tag{2}$$

For purposes of analog classification for 24-hour intensification, the deviation in intensification from that of the test case between time = 12 and time = 24 had to fall within a set of class limits. For 48-hour intensification, the deviations for each 12-hour period involved (24 to 36 and 36 to 48 hours) had to fall within one particular set of class limits. Similar restrictions were placed on the analog classification for the 72-hour intensification. Classification for the 12-hour period remained unchanged. Compared to the original definitions of intensification, these definitions would require more time-restricted relationships to exist between the analog elements and intensification in order for the desired trend of decreasing degree of element matching with increasing forecast error to appear with any persistence. As an example, for an element to exhibit a strong relationship to 48-hour intensification, the relationship would have to be valid during more precisely defined

time limits (24 to 48 hours). Under the prior definitions of intensification, an indicated relationship between the behavior of an element and the 48-hour intensification could have been actually very strong for the first 24 hours, but relatively weak for the second 24 hours. However, these restrictions were considered more favorable than to contend with the identical classification of analogs exhibiting highly variable intensifications.

The first 15 test cases were rerun using the modified definitions of intensification, and the results evaluated again. Little if any change from the previous results were observed. In most cases the average ranks of all the elements were very high, generally greater than 85. This was due to the use of the element ranges in the equation for the ranks. The computed ranges were usually the result of extreme and uncommon element values. For example, the range of sea-level pressure extended from 875 mb to 1012 mb. To compensate for this, the standard deviations of the analog element distributions over the entire data file were computed and substituted for the ranges. With the use of the standard deviations, negative ranks would result when the difference in values of an element was greater than the standard deviation of the element distribution. A closer match of an analog element to its test cyclone value would result in a more positive rank.

A third run of the first 15 test cases revealed no positive results. Plots of the average rank versus forecast

error revealed a much more variable pattern than previously observed, but no consistent decreasing degree of matching with increasing forecast error resulted for any of the analog elements. Many cases revealed extreme oscillations of the average ranks of some elements from one class of analogs to the next.

Only one relationship persisted throughout the entire study to this point. In almost every instance for any analog element in any analog class, a larger average rank was associated with a smaller standard deviation of the element ranks involved. Only a small increase in an average rank was generally accompanied by a small decrease in the standard deviation. Therefore, lower average ranks were associated with relatively more variable individual ranks, but higher average ranks were associated with less variable individual ranks.

The fact remained, however, that both high and low average ranks were observed in all classes of analogs for all 15 test cases. It was felt that if some persistent and useful trend were to develop, at least some weak indications would have resulted by this point in the research. In the absence of any such indications, this method of analog classification and element ranking was abandoned. The possibility existed that the ranking procedure utilized was too sensitive for the accuracy of the data involved and for the reliability and persistence of some relatively weak, but

somewhat useful relationships which might exist. It was decided to attempt a less restrictive classification procedure and to adopt a less refined ranking technique.

E. SECOND APPROACH TO THE OBJECTIVE

The two basic operations of the first approach were also utilized in this procedure. The test cyclone definition and analog selection phase was modified in two ways. First, the initial intensity limits for the analog screening were expanded to plus or minus 40 knots from the initial intensity of the test case. It was felt that a greater number of analogs would generate better results, as has been observed with the TYFOON analog scheme. Due to possible diurnal effects on the results, the 12-hour forecast was excluded and the 24-hour intensification redefined as

$$\Delta I_{24} = I_{24} - I_0 \qquad (3)$$

The analog classification and element rank computation were completely re-developed for this procedure. For analog classification, the deviations in intensification during the 24-hour periods of initial time to 24 hours, 24 to 48 hours, and 48 to 72 hours were considered. The deviations within the individual 12-hour periods contained in these 24-hour periods were not considered in order to make the classification less restrictive and to eliminate possible diurnal effects. For each forecast period (24-, 48-, and 72-hours),

the analogs that intensified within plus or minus 10 knots of the test case per 24-hour period were identified and classified together.

The next step was to assign a rank to each element of the classified analogs. Rather than define a degree of matching for each individual element, a technique was developed that would indicate a match or non-match result for each element and all matches would be given equal weight. It was necessary to establish for each analog element an interval, centered on the test case value, within which an analog candidate value would have to occur to be considered a match. If a match occurred, the element of the analog was assigned a rank of 1.0. If a match failed to occur, the element was assigned a rank of 0.0.

Due to the variable ranges of possible values among the analog elements each established interval of acceptance had to be unique to a particular element. Since the standard deviation of a data population indicates the variability of the quantity, the interval of acceptance was made proportional to this measure of dispersion. An interval of plus or minus one fourth of a standard deviation centered on the test case value was selected as the interval of acceptance for each analog element. All analog element values occurring within this range were considered a match; all others were rejected. The acceptance intervals for the analog elements are given in Appendix C.

For each element the number of occurrences of missing data associated with the classified analogs was determined. Subtracting these numbers from the total number of analogs in the class resulted in the number of possible matches for each element. By summing up the ranks associated with a particular element over all the classified analogs, the number of matches was determined. Dividing this by the number of possible matches and multiplying by 100 resulted in the percent number of matches for the element. This quantity was now referred to as the degree of matching. This procedure was applied and a degree of matching established for each of the 18 elements.

The classification procedure was now repeated for all the analogs that exhibited an intensification within plus or minus 20 knots of the test cyclone per 24-hour period, and for each forecast period. The degree of matching of each element was computed exactly as before. The procedures were again repeated for deviations within plus or minus 30 knots and finally for deviations within plus or minus 40 knots per 24-hour period, for each forecast period.

For each element, the degree of matching versus the maximum allowable class deviation in intensification (maximum allowable forecast error) was plotted. As in the first approach a decreasing degree of matching with increasing forecast error was considered to be indicative of a relationship between element behavior and intensification.

As the maximum allowable forecast error increased from 10 to 40 knots the number of analogs and therefore the number

of possible matches increased. But for a potential predictor, any increased number of actual matches was expected to result in a lower degree of matching.

The procedure was applied to all 30 test cases listed in Appendix B, and the results analyzed. The desired trend of decreasing degree of matching with increasing forecast error was exhibited to at least some extent by all analog elements but much more frequently by some elements.

The next step was to determine the relative significance of each analog element as a potential predictor of intensification. For each forecast period and for each of the analog elements, the number of occurrences of decreasing degree of match with increasing forecast error was noted and the percent of this number to the total possible number of occurrences was computed. These percentages were referred to as indicated forecast potentials. The total possible number of occurrences varied with individual test cases. Some cases contained missing data which ruled out possible matches for some elements and in some cases a future 48- or 72-hour verifying intensity did not exist which prohibited analog classification. The results of these computations are presented in Appendix D.

As a first attempt, it was decided to choose for each forecast period the analog elements associated with the five largest indicated forecast potentials as predictors of intensification for the respective period.

Before developing an experimental forecast scheme, one further step was conducted to provide a more rigorous study of the analog elements.

F. THIRD APPROACH TO THE OBJECTIVE

In order to make the study as thorough as time would allow, various parameters were combined to derive other analog elements to be examined for forecast potential. Also, since it was the change in intensity that was to be forecast, the recent time rates of change of some original and derived elements were investigated for forecast potential. Only the past 24- and 48-hour changes of various parameters were examined, as utilizing any greater amount of history might lead to limitations in a forecast scheme applied to a recently detected cyclone. The derived elements are listed in Appendix E. All but three were easily derivable from the original analog and identify elements of TYFOON.

The three new elements which required some external information were the 1000/700-mb thickness elements. These elements were included as indicators of the thermal characteristics of the lower domain of the cyclones. The minimum 700-mb height above the cyclones and the minimum sea-level pressure (original analog elements) made possible an approximation of the 1000/700-mb thickness.

The missing term for the thickness elements was the height of the 1000-mb surface. It is a widely-held belief that a sea-surface temperature of at least 26-27C is required for tropical cyclone development [5]. The air temperature

near the air-sea interface must be similar to the sea-surface temperature. A mean virtual temperature of 30C for the layer between the surface and 1000 mb was considered a reasonable average approximation. With this approximation, and the use of the hydrostatic equation and the equation of state, the height of the 1000-mb surface could be estimated.

$$\partial P = -g\rho\partial z \tag{4}$$

$$P = \rho RT \;, \qquad \rho = \frac{P}{RT} \tag{5}$$

$$\frac{\partial P}{P} = \frac{-g}{RT}\,\partial z = \partial(\ln p) \tag{6}$$

$$\int_{P_{sfc}}^{1000} \partial(\ln p) = \frac{-g}{RT} \int_{0}^{Z_{1000}} \partial z \tag{7}$$

$$\ln 1000 - \ln P_{sfc} = \frac{-g}{RT}\, Z_{1000} \tag{8}$$

$$Z_{1000} = (\ln P_{sfc} - \ln 1000)\,\frac{RT}{g} \tag{9}$$

$$Z_{1000} = K_1 \ln P_{sfc} + K_2 \tag{10}$$

Z = height (m)

P = pressure (mb)

T = virtual temperature (K)

R = gas constant = 2.87×10^6 erg/gm/K

g = gravity = $9.80\ m/sec^2$

$K_1 = \frac{RT}{g}$

$K_2 = -\frac{RT}{g}(\ln 1000)$

The 1000-mb height thus obtained was subtracted from the minimum 700-mb height above the vortex to determine the

thickness. In this manner, the current, past 24-hour and past 48-hour thicknesses were computed and the appropriate time rates of change calculated.

The investigative procedures conducted on these derived elements were essentially identical to those applied to the original elements and described in the previous section. Some program modifications were necessary, however.

In the test cyclone definition and analog selection phase, the necessary past 24- and 48-hour data were defined and a routine was added to compute the time rates of change. A history indicator was also defined for each test cyclone to indicate the extent to which history elements of the selected analogs should be calculated. This phase was also modified to compute the necessary and available derived elements for each selected analog.

Only one modification was necessary for the analog classification and element rank computation phase. It was necessary to redefine the matching criteria (acceptance intervals) for the new elements. To compute the standard deviations of all the elements would have required more computer time than was practically available. Acceptance intervals were defined subjectively based on the estimated variability of each element and on the estimated probable errors in the values. As before the intervals were centered on the test cyclone element values, and for an analog element to be accepted as a match, its value had to occur in

the appropriate interval. The acceptance intervals for the derived elements are listed in Appendix E.

The procedures were carried out on the 30 test cases listed in Appendix B and an analysis of the results was made as described in the previous section. For each forecast period, the indicated forecast potential was computed for each element, and the elements associated with the five largest indicated forecast potentials were selected as predictors of intensity. The indicated forecast potentials of the derived analog elements are listed in Appendix F.

With the intensity predictors defined, it was now necessary to establish their relative importance for use in a forecast scheme.

G. DERIVATION OF WEIGHT FACTORS FOR SELECTED PREDICTORS

The results of the study to this point revealed that the potential among the original and derived analog elements as predictors of tropical cyclone intensification varied greatly. For the elements that were selected as predictors, in a forecast scheme, more emphasis would be placed on those that exhibited more persistently the trend of decreasing degree of matching with increasing forecast error. The degree of emphasis placed on each predictor would be indicated by a weight factor. Out of ten predictors, for example, it would not suffice to assign the best one a weight of ten and the worst one a weight of one. This would imply that the best predictor possesses ten times the forecast potential of

the worst one, whereas it may only possess twice as much. Therefore it was necessary to derive weight factors as a function of the indicated forecast potentials resulting from the earlier investigations.

To assign weight factors relative to the indicated results, the following procedures were applied. First of all, a small number of selected predictors were eliminated due to their close relationships to other predictors with equal or higher indicated forecast potentials. This avoided a concentrated emphasis on the related predictors, the cumulative effect of which, might often lead to poor results. For each forecast period the selected predictor (original or derived) with the lowest indicated forecast potential was assigned a weight factor of 1.0. The weight factors for the other predictors for each period were computed by dividing the values of the associated indicated forecast potentials by the lowest potential for the respective forecast period. This procedure normalized the numerical weight factors based on the smallest value of an indicated forecast potential for each period. The selected predictors and their respective weight factors are listed in Appendix G.

At this point, the primary objective of the study was accomplished. An examination of the potential value of the analog elements as predictors of intensification was made; a number of predictors was selected for each forecast period and associated weight factors derived. To test the findings of this part of study and to evaluate the merit of the

procedures utilized for identifying useful predictors, a forecast scheme was developed.

H. DEVELOPMENT OF A FORECAST SCHEME

The forecast scheme to be developed could function in many different ways. A weighted average intensification of all the selected analogs could be computed as a forecast, or a filtering technique could be applied to all the analogs to determine those which most closely resembled the test cyclone and apply the intensifications of these filtered analogs as a forecast. A scheme of the latter type was devised, as the actual forecast potentials of the predictors would be more directly utilized. The following forecast scheme was developed and applied to the 30 dependent cases used to select the predictors.

The test cyclone definition and analog selection operation was identical to that developed for analyzing the derived elements with one addition. For each forecast period (0-24, 24-48, 48-72 hours), the maximum positive and negative intensifications exhibited by the selected analog candidates were determined.

The second operation constituted the actual forecast scheme. The 24-hour forecast was first determined. All selected analogs were classified according to their 24-hour intensification. The analogs that intensified between -5 and +5 knots, inclusive, were classed together and assigned a characteristic intensification of zero. Next, all analogs

that intensified between +5 and +15 knots were classed together and assigned a characteristic intensification of +10 knots. Analogs that exhibited an intensification of +5 knots were assigned to both classes as the data were not accurate enough to warrant a rigid delineation between classes. The procedure was repeated until all the intensifying analogs were classified. Next, all the analogs exhibiting negative intensification were classified in a similar manner. One of the resulting characteristic intensifications would be selected as a forecast.

The characteristic intensifications and the number of analogs classed with each were printed out. The distribution of the analogs among the classes indicated the most to least frequently occurring intensifications of all past six-hourly reports of all past tropical cyclones exhibiting a time of occurrence, position, and initial intensity similar to those of the test cyclone. The distribution therefore represented an intensification climatology of a precisely defined group of tropical cyclone reports. The characteristic intensification of the class containing the largest number of analogs was defined as the modal intensification.

For each predictor, the degree of matching was determined for each analog class. As before, the degree of matching was defined as the number of actual matches relative to the number of possible matches. The matching criteria

(acceptance intervals) were those utilized in the selection of the predictors. The analog class that exhibited the highest degree of matching for each predictor was determined, and the weight factor associated with that predictor was assigned to that class of analogs. If two or more classes exhibited the same degree of matching for a predictor, the weight factor was assigned to all of those classes. The assigned weight factors for each class were then summed and the summation for each class was printed out. These same procedures were then applied to the 48- and 72-hour forecast periods.

Originally, it was the intention to select the characteristic intensification associated with the largest summation of weight factors as the forecast. However, analysis of early results revealed a problem area and a previously overlooked factor: the variable probability of chance element matching. The numbers of analogs associated with the different classes varied from as few as one to ten, to as many as 80 to 100, as an example. In most cases, the classes containing relatively very few analogs resulted in relatively very large weight factor summations. The trend was so persistent that some unaccounted-for factor was suspected to be influencing the results. It was believed that the smaller the number of analogs in a given class, the greater was the probability of getting element matching due to pure chance. The implications of this factor are

discussed further in the results section and only the procedures attempted to account for chance matching are stated here.

To compensate for the chance matching factor, it was necessary to account for the number of analogs in each class. Simply multiplying the weight factor summation of each class by the number of associated analogs would not suffice, because the ranges and orders of magnitude of the numbers of analogs were much larger than those of the weight factor summations. The results would be almost totally functions of modal intensification. To reduce the effects of the number of analogs in each class on the results, the square roots of these numbers were computed and multiplied by the respective weight factor summations. This procedure alleviated the problem of chance matching to a large degree, but in many cases in which there were extremely large variations in the numbers of analogs among the classes, the problem still persisted. Therefore it was decided to eliminate, as possible forecasts, the characteristic intensifications of classes with relatively very few analogs. In order to maintain a strictly objective forecast scheme, a definite procedure was needed to select those classes whose characteristic intensifications would be retained for the forecast determination. Only those characteristic intensifications whose frequencies of occurrence were in the upper 50 percent of the entire distribution were retained. That is, the classes were selected in order of decreasing number of

associated analogs until one half of the total number was selected, unless an equal number of analogs in two or more classes required more than one half of the total. The development of this procedure was purely subjective, but it did provide for an objective determination of a forecast, and a complete revision of the forecast scheme in order to account for chance matching was impractical at this time.

For each test case, three forecasts were derived based on different criteria:

1) modal intensification: characteristic intensification associated with the largest number of analogs

2) weighted predictors: characteristic intensification associated with the largest weight-factor summation (after elimination of specified analog classes)

3) weighted climatology: characteristic intensification associated with the largest product of weight-factor summation and square root of the number of associated analogs (after elimination of specified analog classes).

For each method the 24-hour intensification was determined and added to the initial intensity to obtain the 24-hour forecast intensity. Then the 24- to 48-hour intensification was determined and added to the 24-hour intensity to obtain the 48-hour forecast intensity. The 72-hour intensity was determined similarly. A minimum forecast intensity of 30 knots was imposed on each forecast method. This was done to reduce the degrading effects of a highly underforecasted 24-hour intensity, for example, on the 48- and 72-hour forecast

intensities which might otherwise be very accurate. The resulting forecasts were compared to the official JTWC forecasts issued for the 30 test cases. The forecast scheme was then applied to 62 more independent test cases selected using the same criteria for the original 30 test cases. These test cases are listed in Appendix H. The results of these forecasts were also compared to official JTWC forecasts. A discussion of the forecast results and the results of the study in general is given in the next section.

III. RESULTS AND CONCLUSIONS

A. DISCUSSION OF SELECTED PREDICTORS

No attempt was made to justify rigorously, using either meteorological principles or statistical testing, the analog elements that exhibited high indicated forecast potentials and thus were selected as predictors. There are, however, some obvious results and trends worth noting. See Appendix G for the selected predictors for each forecast period.

Extrapolation of past intensity changes in operational forecasts has been used extensively and has been shown to produce reliable results for short-term forecasts. Of the derived elements, the one exhibiting the highest indicated forecast potential for the 24-hour forecast was the past 24-hour change in intensity. This element was also selected as a predictor for the 48-hour forecast period, but it exhibited a lower indicated forecast potential than it did for the 24-hour forecast period. For the 72-hour forecast period, no past intensity change elements exhibited large enough forecast potentials to warrant selection as predictors. This trend agrees with the fact that extrapolation of past intensity changes in operational forecasting has given more accurate results for the short-term forecasts.

The results indicated that the height and latitude of the 700-mb subtropical ridge at the longitude of the cyclone were related to intensification during all forecast periods.

Of all the original and derived elements, these quantities and derivatives involving them appeared as predictors the most persistently. The resulting weight factors of predictors involving these quantities generally increased in the most extensive forecast period. For example, the weight factors derived for the 700-mb ridge latitude increased from 1.12 and 1.13 for the 24- and 48-hour forecast periods to 1.52 for the 72-hour forecast period. The derived analog element involving the difference in 700-mb heights of the ridge and cyclone divided by the difference in latitude showed a similar trend. It was not designated as a 24-hour predictor, but the weight factor associated with this element increased from 1.13 for the 48-hour period to 1.33 for the 72-hour period. The past 24-hour change in this predictor also exhibited weight factors increasing with the forecast period, e.g., from 1.18 to 1.37 to 1.81 in the 24-, 48-, and 72-hour forecast periods, respectively.

The past 12-hour speed of movement element displayed decreasing indicated forecast potentials from the 24- to 72-hour forecast periods and was defined as a predictor for only the 24- and 48-hour periods. The weight factors associated with this predictor decreased from 1.42 for the 24-hour forecast to 1.07 for the 48-hour forecast. The past 24-hour speed of movement element was selected as a predictor for the 72-hour period, but possessed the lowest weight factor for that period.

The 700-mb trough height and the past 24-hour change in this quantity dominated the 48-hour forecast predictors, in that they possessed the two highest indicated forecast potentials and associated weight factors. The 700-mb trough height also possessed the highest indicated forecast potential of any of the original analog elements for the 72-hour forecast period.

The estimated 1000/700-mb thickness element was not itself defined as a predictor for any of the forecast periods. However the past 24- and 48-hour changes of this element did exhibit sufficient indicated forecast potentials to be designated as predictors. There was little observable trend in the indicated forecast potential of these predictors from one forecast period to the next. The past 48-hour change in thickness was defined as a predictor for the 24-hour period; no thickness elements were defined as predictors for the 48-hour period; the past 24-hour and again the past 48-hour changes in thickness were designated predictors for the 72-hour period.

It is also interesting to note that the minimum 700-mb height above the cyclone was defined as a predictor for the 24-hour forecast period only. However, derived elements involving this quantity were designated as predictors for all forecast periods.

The elements designated as predictors from the results of this study are not necessarily considered to be the

actual best predictors of tropical cyclone intensification among the possibilities derivable from the data. An almost infinite number of combinations of the original 18 analog elements could be evaluated as possible predictors. As will be discussed later, the results of just those elements considered in this study could be altered by modified and improved procedures.

B. FORECAST VERIFICATION AND RESULTS

1. Results of All Dependent Test Cases

The analog forecasts derived for the 30 dependent and 61 independent test cyclones, as well as the available official JTWC forecasts supplied by FWC Guam were verified on the basis of two main criteria: (1) absolute value of the forecast intensity errors; (2) the algebraic and absolute values of forecast intensity errors relative to the verifying intensities and expressed as percent errors. The first of these criteria is of little practical value in an operational forecast procedure. It considers only the magnitude of the error without regard to the actual magnitude of the cyclone intensity. For the purposes of operational forecasting and contingency procedures of all concerned activities, a 20-knot error in a 24-hour forecast, for example, would be considered misleading and inadequate for a tropical storm with a verifying intensity of 40 or 50 knots. The same error for the same forecast period, however, would be considered adequate for a super typhoon with a verifying

intensity of 130 knots [3]. Therefore it is the relative forecast error that is of primary concern. The Joint Typhoon Warning Center has established relative error acceptability criteria for different forecast time periods. The criteria for the 24-, 48- and 72-hour forecast periods are defined in [3] and are presented in Table I. The criteria are relaxed for more extended forecast periods as contingency requirements are more flexible over longer time periods [3]. Average values of the absolute intensity errors are provided only to indicate to what extent the error magnitudes vary from one forecast period to the next and to provide an additional comparison of the analog forecasts to those of JTWC. The analog forecast results are presented for all three forecast methods:modal intensification, intensification based on weighted predictors, and intensification based on weighted climatology (weighted combination of first two methods).

Table II and Table III present the average absol te forecast errors for all of the dependent and indcpendent test cases, respectively. Generally for both set of cases, t ie largest increase in errors from the 24- to 72-hour forecast periods occurred between the 24- and 48-hour forecast periods. Relatively little forecast deterioration was observed between the 48- and 72-hour periods. This trend was exhibited by all forecast methods with two exceptions: the modal intensification for the dependent cases and the weighted climatology intensification for the independent cases.

Table IV and Table V provide the 24-hour relative forecast errors for the dependent and independent test cases. For the dependent cases the weighted climatology produced the best results, but for the independent cases, modal intensification was generally the most accurate. For the weighted predictors and weighted climatology intensifications, the results deteriorated to varying degrees in going from the dependent to the independent test cases. But for the modal intensification, the results of the independent cases showed improvement over those of the dependent cases, with the exception of the 10% error category.

For both the dependent and independent test cases, the weighted predictors intensification showed the greatest fraction of useful forecasts ($\leq$ 30% error) that were accurate to the measurement of the data ($\leq$ 10% error). For example, considering the dependent cases, (Table V), this forecast method resulted in 75%(50/67=.75) of the useful forecasts being accurate to the measurement of the data. These percentages for the modal and weighted-climatology intensifications for the dependent cases were 55% and 62%, respectively. This indicates that although the weighted-predictors intensification did not produce as many useful forecasts as the other methods, it became relatively more skillful than the other methods as the forecast error decreased.

The 48-hour relative forecast errors are presented in Table VI and Table VII. The modal intensification and

that of weighted climatology exhibited nearly the same results, especially for the useful ($\leq$ 40% error) and adequate ($\leq$ 30% error) forecast categories. All forecast methods suffered deterioration in going from the dependent to independent test cases. The modal intensification exhibited the largest fraction of useful forecasts that were accurate to the measurement of the data for both sets of test cases. The weighted predictors showed the smallest fraction for the dependent cases while the weighted climatology showed the smallest fraction for the independent cases.

The relative forecast errors for the 72-hour forecast period are presented in Table VIII and Table IX. For the dependent cases, the best results were observed for the modal and weighted climatology intensifications, while modal intensification dominated with the independent tests. Again the results generally deteriorated from the dependent to independent cases for all forecast methods, but to a lesser extent for the modal intensification. The modal intensification again exhibited the largest fraction of useful forecasts that were accurate to the measurement of the data for both sets of test cases. As with the 48-hour forecasts, the weighted predictors showed the smallest fraction for the dependent cases, and the weighted climatology showed the smallest fraction for the independent cases. The fraction associated with the weighted predictors showed an increase from the dependent to independent test cases (16/64 = .25 to 16/55 = .29).

Table X presents the relative forecast errors of the independent test cases stratified by initial intensity. Two error categories are presented -- those that resulted in inadequate forecasts, and those that resulted in forecasts accurate to the measurement of the data. The test cases were stratified on the basis of whether or not their initial intensities were of typhoon strength. For the 24- and 48-hour forecast periods the number of occurrences of inadequate forecasts was substantially less for the typhoon cases than it was for the storm or depression cases for each of the three forecast methods. But for the 72-hour forecast period the results were much more similar for the modal intensification, and essentially identical for the remaining two methods. The number of forecasts accurate to within data measurements for each forecast period was generally greater for the typhoon cases than for the storm or depression cases. For the 24-hour forecast period the number of forecasts accurate to the measurement of the data was significantly greater for the typhoon cases than for the depression or storm cases for each forecast method. Except for the modal intensification, this stage-related trend decreased substantially in the more extended forecast periods. These results imply that the intensifications of the more intense tropical cyclones are generally more predictable than those of the weaker, developing or dying, depressions and storms. The results in Table X are based on relative errors, and therefore do not imply that the absolute forecast errors

decrease with increasing initial intensity. But as stated previously, an absolute error of 20 knots is not nearly as significant for a 130-knot typhoon as it is for a 40- to 50-knot storm. Therefore, if it is accepted that only relative errors are meaningful, the implications of the results in Table X are valid.

Frequency histograms of relative errors for the three forecast methods were constructed for both dependent and independent test cases. The histograms for the weighted-climatology forecast method are representative of all those constructed and are presented in Figures 1 through 6. In all cases, relative errors of $\pm$ 5% or less were classified as zero forecast error. For positive errors, N% error included all errors within (N-4)% and (N+5)% inclusive, and for negative errors, -N% error included all errors within (-N+4)% and (-N-5)%, inclusive. Therefore the results presented in the histograms do not exactly agree with those presented in the tables.

The histograms for the dependent cases reveal that the forecast ability of the weighted-climatology method decreased from the 24- to 48- to 72-hour forecast periods. That is, the numbers of occurrences of small relative forecast errors ($\leq$ 20%) decreased and the distribution became more variable for the more extended forecast periods. No persistent skewness toward positive or negative errors resulted. However it was observed that the largest forecast errors were consistently positive errors.

The results for the independent test cases differed somewhat from the dependent cases. The most obvious difference was the persistent skewness toward negative forecast errors, especially in the 24- and 48-hour forecast periods. The fact that this result did occur might have made possible the use of an adjustment factor or function to modify and improve the results. This was not attempted, however, in this study. The histograms reveal a decrease in the number of occurrences of small forecast error with increasing forecast periods. One similarity of these results to those of the dependent cases was the fact that the largest errors were consistently positive errors.

2. <u>Comparison of Analog Forecasts to Official JTWC Forecasts</u>

As a further measure of the significance of the forecast results, comparisons of the analog forecasts to those of the official JTWC forecasts were made for homogeneous sets of dependent and independent test cases. Comparisons were made for the 24- and 48-hour forecast periods only due to the very limited number of applicable 72-hour forecasts available from FWC Guam. The analog results were recomputed based on only those test cases for which the official forecasts were available.

The average absolute forecast errors are presented in Table XI and Table XII for the dependent and independent tests,respectively. As the figures indicate, the average errors resulting from all three analog methods were from 35%

less than, to at worst equal to those of the official forecasts for the dependent test cases. For the independent cases, the errors for the analog forecasts were from 17% to almost 60% greater than official forecast errors. The weighted predictors method gave the worst results for the independent cases. Neglecting this method, the largest percent increase in error was 33% (for the weighted climatology). The overall best results, considering both forecast periods and both sets of test cases, were produced by the modal intensification. However, the weighted predictors and weighted climatology did result in smaller average forecast errors for the 24-hour dependent forecasts than did the modal intensification.

Table XIII shows the comparisons of relative forecast errors among the analog methods and the JTWC forecasts for the dependent tests. These results reveal that all of the analog methods exhibited some equal or superior foreca t ability over the official forecasts. Exceptions were the modal and weighted-predictors 24-hour forecasts for the $\leq$ 30% error category, and the weighted-predictors 48-hour forecasts for the $\leq$ 20% and $\leq$ 10% error categories. All but one of the analog methods exhibited a greatest fraction of useful forecasts that were accurate to the measurement of the data for both periods than did the official forecast. This indicates that as the forecast error decreased, the analog methods (with one exception) became relatively more

skillful than did the official forecasts. The one exception to this result was the weighted predictors intensification for the 48-hour period only. However, the fraction exhibited by the weighted predictors method for the 24-hour forecast period was substantially greater than any of the others.

The relative error comparisons for the independent test are shown in Table XIV. For the most part, the official forecasts proved to be superior to the analog forecasts. Exceptions were the 24-hour weighted climatology forecasts for the $\leq$ 10% category error category and the 48-hour modal and weighted climatology forecasts for the $\leq$ 10% error category. For all analog methods for both forecast periods, the superiority of the official forecasts decreased with decreasing error categories from $\leq$ 30% to $\leq$ 10% errors. However, the trend is just the opposite in going from the $\leq$ 40% to $\leq$ 30% error categories. With one exception, the fractions of the useful forecasts that were accurate to the measurement of the data were greater for the analog forecasts than for the official forecasts. Again, the exception was the weighted predictor method for the 48-hour forecast period.

C. CONCLUSIONS

1. Implications of Forecast Results

The overall results of the forecast verification are considered competitive with official forecasts and thus encouraging. The general deterioration of the results from

the dependent to independent test cases was expected; nonetheless substantial numbers of useful and adequate analog forecasts were generated for these independent cases. The results were especially encouraging for the 48- and 72-hour forecasts, as these extended periods offer the forecaster the greatest challenge. If these results were maintained under conditions of operational forecasting, they would at least provide the forecaster with a starting point, other than linear extrapolation and climatology, for deriving his prediction. With a somewhat reliable starting point, the finished forecast might well be more accurate.

Of the three analog forecast methods applied, those involving the use of various analog elements possess the greatest potentials for improvement. Modal intensification might be improved slightly by experimenting with the screening criteria, but little else could be done to reduce the forecast errors. However, an almost unlimited amount of experimentation with the analog elements and their forecast potentials is possible.

It has been established that the analog forecast methods performed more accurately on test cases used to derive the predictors and their associated weight factors. The analog elements associated with the small sample of test cases utilized for this purpose undoubtedly are not representative of all the element distributions. However, if all available past data were utilized in deriving the

predictors and their weight factors, the resulting distributions of the analog elements would be very representative of the possible values that each element could assume. Therefore, the likelihood would be high that all but extremely uncommon cyclones (for which forecasts must be issued), would resemble at least some cyclones used to derive the predictors and weight factors. Consequently, the relationship of any given current cyclone to the information used in deriving the forecast scheme would approach the relationship between the dependent test cases and the information used in deriving their forecasts. Thus it is strongly believed that more accurate results could be obtained by increasing to the maximum extent the number of test cases utilized in deriving the predictors and their weight factors.

As stated earlier, the number of elements derivable from the original 18 analog elements is enormous. Evaluation of elements other than those considered in this study might well lead to potentially better predictors and forecast results. Also the technical procedures of element evaluation and forecasting could be modified, or completely different avenues of approaches followed.

2. Evaluation of Investigative Procedures

The encouraging results of the analog forecasts derived in this study strongly suggest that the methods utilized in defining the predictors and computing associated weight factors possess at least some degree of skill. In spite of some crude and intuitively derived procedures

involved in the method, the resulting predictors apparently do possess at least some degree of forecast potential. Examples of these crude procedures are the definitions of the acceptance intervals for original and derived element matching. A "sledge hammer" effort was also applied in the forecast method to alleviate the problems of variable chance element matching.

The most severe shortcoming of the methods utilized was the failure to properly account for the variable probability of chance element matching. The effects of this factor were not realized until forecast outputs were analyzed. However, it is likely that the same distorting effects were present in the element investigation procedures.

In the second and third approaches to the main objective, the selected analogs were classified on the basis of a maximum allowable deviation in intensification from that of the test case. First, all analogs that intensified within $\pm$ 10 knots per 24-hour period were classified and the degree of element matching determined. Then all analogs that underwent a change in intensity of $\pm$ 20 knots, $\pm$ 30 knots and finally $\pm$ 40 knots per 24-hour period were classified and for each maximum allowable intensification deviation, the degrees of element matching were computed. It is obvious that as these deviations increased, the number of acceptable analogs increased, which in turn, generally increased the number of possible analog element matches.

For a particular analog element, a population could be defined as the entire set of values for that element contained in the complete data file. The different classes of analogs represent samples of various sizes of this element population. Generally as the number of analogs increased, with increasing intensification range, the size of the element samples also increased. The variable sample sizes is one factor of the chance element matching.

The other factor is the location, within an element population, of the value of the test case analog element. That is, in general, the farther (closer) the test case value is from the expected (i.e. mean) value, the smaller (greater) the probability of getting a match by pure chance.

In the procedures of this study, the degree of matching was defined as the percent of matches to the total number of possible matches. However, the ratio involved in this computation can also be considered an average of ranks. This ratio is nothing more than the sum of ranks (0 or 1) divided by the number of ranks.

The Central Limit Theorem can be applied to this problem. The implications are that as the sample size increases, and as the test cyclone element value departs the expected value in the element population, the smaller the probability that a specified average rank (e.g. .50) will occur due to chance alone. This implies a smaller probability of a specified degree of matching (e.g. 50%) due to

chance as the sample size increases. But as the sample size increases and as the test case element value approaches the expected value in its distribution, the greater the probability of a specified average rank due to chance. This implies a greater probability of a specified degree of matching,due to chance alone, as the sample size increases. The significance of a match varies with the location of the test case element value in its distribution. To account for this, the size of the acceptance interval should vary from smaller magnitudes in high density regions of the population to larger magnitudes in low density regions.

To properly compensate for chance element matching, both the analog class sizes and the location of the particular test case element value within its population must be accounted for. This requires a thorough study of the distributions of all predictors to be utilized.

Since chance matching could tend to increase the degree of matching for both large and small analog classes (depending on the location of the test case element value in its population), the procedures taken in this study to compensate for chance matching were only partially valid. The procedures were proper only when the test case element values were in low density regions of their distribution.

Regardless of the shortcomings of the procedures in this study, the results warrant further study into the potential of analog schemes in forecasting tropical cyclone intensification. It is felt that concentrated efforts in

this area could lead to improved and more significant results, and the evolution of a reliable and efficient intensification forecast aid.

3. Thoughts on Subsequent Studies

In all the investigative and forecast procedures utilized in this study, the first operation was to screen out those six-hourly reports of past tropical cyclones that exhibited similarity to the test case with respect to location and time of occurrence. Further screening criteria then determined those analog candidates that resembled the test case with respect to the analog elements. The ideal analog procedure would be to continue the screening criteria until one analog candidate was defined to be the most similar to the test case. This ideal procedure would require that the data observations be exact. It would also be necessary to know exactly what parameters are the ideally best predictors. These ideally best predictors would have to possess precise relationships to intensification, and the relationships would have to hold true for all cyclone occurrences. In reality the data are not exact, and reliable predictors with precise relationships to intensification have not yet been defined. This forces the analog technique to rely on average behavior in order to generate a quantitative forecast. With the use of averages, it is hoped that random observational errors and non-persistent relationships will be smoothed to a degree that enables the

utilization of the data in an adequate forecast scheme. Indeed, if the data were exact and precise relationships between predictors and intensification were known, deterministic techniques would replace statistical schemes. To generate a forecast, it would be necessary to simply substitute predictor values in an equation and solve for the intensification.

It is felt, however, that some efforts should be made to strive for a more ideal analog forecast technique, involving more sophisticated screening criteria aimed at reducing the number of analog cyclones used in generating the forecast. A continuous-type degree of matching criterion was attempted in the first approach of this study. Due to the inconclusive results of this procedure, a match, no-match criterion was investigated. A combination of these two matching criteria might lead to better results. That is for each analog element apply a match, no-match screening procedure to eliminate grossly unmatched values, and to identify those values within some prescribed range from the test case value. With a large degree of noise eliminated, then proceed with a continuous-type degree of matching operation. For example, the difference in element values relative to the magnitude of the acceptance interval (used in the first step) could be examined. This type of procedure could possibly define more precise and persistent relationships between analog elements and intensification than those which were defined in this study. With the use

of more precise relationships, the screening procedure in the forecast scheme could be more restrictive and thereby select a fewer number of analogs that are more similar to the test case with respect to predictor values. In any event, further studies might reveal to what extent average behavior must be relied upon to smooth out the data errors and non-precise and quasi-persistent relationships.

TABLE I

Forecast-intensity relative error acceptability criteria, as defined by JTWC.

E = forecast-intensity error relative to verification intensity

Forecast Value	Forecast Period	
	24-hour	48- and 72-hour
Accurate to within intensity measurement error	$E \leq 10\%$	$E \leq 10\%$
Adequate	$E \leq 20\%$	$E \leq 30\%$
Useful	$E \leq 30\%$	$E \leq 40\%$
Inadequate	$E > 30\%$	$E > 40\%$

TABLE II

Average absolute forecast-intensity errors (kt) for all dependent test cyclones. Numbers in parentheses indicate the number of applicable forecasts for each forecast period.

Forecast Period (Hr)	Modal	Forecast Method Weighted Predictors	Weighted Climatology
24 (30)	16	13	13
48 (29)	16	23	20
72 (25)	19	23	21

TABLE III

Average absolute forecast-intensity errors (kt) for all independent test cyclones. Numbers in parentheses indicate the number of applicable forecasts for each forecast period.

Forecast Period (Hr)	Modal	Forecast Method Weighted Predictors	Weighted Climatology
24 (61)	16	19	26
48 (59)	26	28	28
72 (51)	28	33	32

TABLE IV

Percent of all dependent test cyclones exhibiting the indicated relative error (E) in the 24-hour forecast intensity. Results based on 30 forecasts.

E = forecast-intensity error relative to verification intensity.

Forecast Method	E(%)			
	≤ 40	≤ 30	≤ 20	≤ 10
Modal	87	73	57	40
Weighted Predictors	83	67	63	50
Weighted Climatology	90	80	70	50

TABLE V

Percent of all independent test cyclones exhibiting the indicated relative errors (E) in the 24-hour forecast intensity. Results based on 61 forecasts.

E = forecast-intensity error relative to verification intensity.

Forecast Method	E(%)			
	≤ 40	≤ 30	≤ 20	≤ 10
Modal	90	82	64	31
Weighted Predictors	79	66	54	38
Weighted Climatology	84	74	54	36

TABLE VI

Percent of all dependent tests cyclones exhibiting the indicated relative errors (E) in the 48-hour forecast intensity. Results based on 29 forecasts.
E = forecast-intensity error relative to verification intensity.

Forecast Method	E(%)			
	≤ 40	≤ 30	≤ 20	≤ 10
Modal	79	70	59	41
Weighted Predictors	70	59	43	21
Weighted Climatology	76	70	59	34

TABLE VII

Percent of all independent test cyclones exhibiting the indicated relative errors (E) in the 48-hour forecast intensity. Results based on 59 forecasts.
E = forecast-intensity error relative to verification intensity.

Forecast Method	E(%)			
	≤ 40	≤ 30	≤ 20	≤ 10
Modal	71	54	44	23
Weighted Predictors	64	49	30	20
Weighted Climatology	68	54	34	15

TABLE VIII

Percent of dependent test cyclones exhibiting the indicated relative errors (E) in the 72-hour forecast intensity. Results based on 25 forecasts.

E = forecast-intensity error relative to verification intensity.

Forecast Method	E(%)			
	≤ 40	≤ 30	≤ 20	≤ 10
Modal	68	56	52	40
Weighted Predictors	64	56	32	16
Weighted Climatology	80	56	36	24

TABLE IX

Percent of all independent test cyclones exhibiting the indicated relative errors (E) in the 72-hour forecast intensity. Results based on 51 forecasts.

E = forecast-intensity error relative to verification intensity.

Forecast Method	E(%)			
	≤ 40	≤ 30	≤ 20	≤ 10
Modal	67	53	43	24
Weighted Predictors	55	41	33	16
Weighted Climatology	59	35	31	16

TABLE X

Percent of all independent test cyclones, stratified by initial intensity, exhibiting the indicated relative errors (E) in forecast intensity. Numbers in parentheses indicate the number applicable forecasts for each criterion.

E = forecast-intensity error relative to verification intensity.

Forecast Method	Initial Intensity (kt)	24-Hour Forecast E $\leq$ 10%		24-Hour Forecast E $\geq$ 30%	48-Hour Forecast E $\leq$ 10%		48-Hour Forecast E $\geq$ 40%	72-Hour Forecasts E $\leq$ 10%		72-Hour Forecasts E $\geq$ 40%
Modal	<64	25	(28)	29	15	(27)	44	18	(22)	37
	$\geq$64	36	(33)	9	31	(32)	16	28	(29)	31
Weighted	<64	32	(28)	39	15	(27)	44	14	(22)	46
Predictors	$\geq$64	42	(33)	24	25	(32)	28	17	(29)	45
Weighted	<64	29	(28)	39	15	(27)	41	14	(22)	41
Climatology	$\geq$64	43	(33)	15	16	(32)	25	17	(29)	41

TABLE XI

Comparison of average absolute forecast errors (kt) of analog forecast methods to those of official JTWC forecasts for a homogeneous set of dependent test cyclones. Numbers in parentheses indicate the number of applicable forecasts for each period.

Forecast Period	Modal	Weighted Predictors	Weighted Climatology	JTWC
24 (25)	14	11	12	17
48 (21)	15	21	20	21

TABLE XII

Comparison of average absolute forecast errors (kt) of analog forecast methods to those of official JTWC forecasts for a homogeneous set of independent test cyclones. Numbers in parentheses indicate the number of applicable forecasts for each period.

Forecast Period	Modal	Weighted Predictors	Weighted Climatology	JTWC
24 (33)	15	19	15	12
48 (25)	21	25	24	18

TABLE XIII

Comparison of relative forecast errors (E) of analog forecasts to those of official JTWC forecasts for a homogeneous set of dependent test cyclones. Figures indicate the percent of test cyclones exhibiting the indicated relative errors. Numbers in parentheses indicate the number of applicable forecasts for each forecast period.

E = forecast-intensity error relative to verification intensity.

	24-Hour Forecasts (25)				48-Hour Forecasts (21)			
	Forecast Method				Forecast Method			
E(%)	Modal	Weighted Predictors	Weighted Clim.	JTWC	Modal	Weighted Predictors	Weighted Clim.	JTWC
≤ 40	92	88	88	88	86	76	86	71
≤ 30	76	72	84	84	76	67	76	67
≤ 20	60	68	72	52	67	52	62	57
≤ 10	44	56	52	24	48	29	48	33

TABLE XIV

Comparison of relative forecast errors (E) of analog forecasts to those of official JTWC forecasts for a homogeneous set of independent test cyclones. Figures indicate the percent of test cyclones exhibiting the indicated relative errors. Numbers in parentheses indicate the number of applicable forecasts for each forecast period.

E = forecast-intensity error relative to verification intensity.

	24-Hour Forecasts (33)				48-Hour Forecasts (25)			
	Forecast Method				Forecast Method			
E(%)	Modal	Weighted Predictors	Weighted Clim.	JTWC	Modal	Weighted Predictors	Weighted Clim.	JTWC
≤ 40	91	72	82	94	88	72	84	92
≤ 30	84	61	73	89	60	48	64	76
≤ 20	61	48	55	67	44	36	48	56
≤ 10	33	33	42	36	28	16	24	24

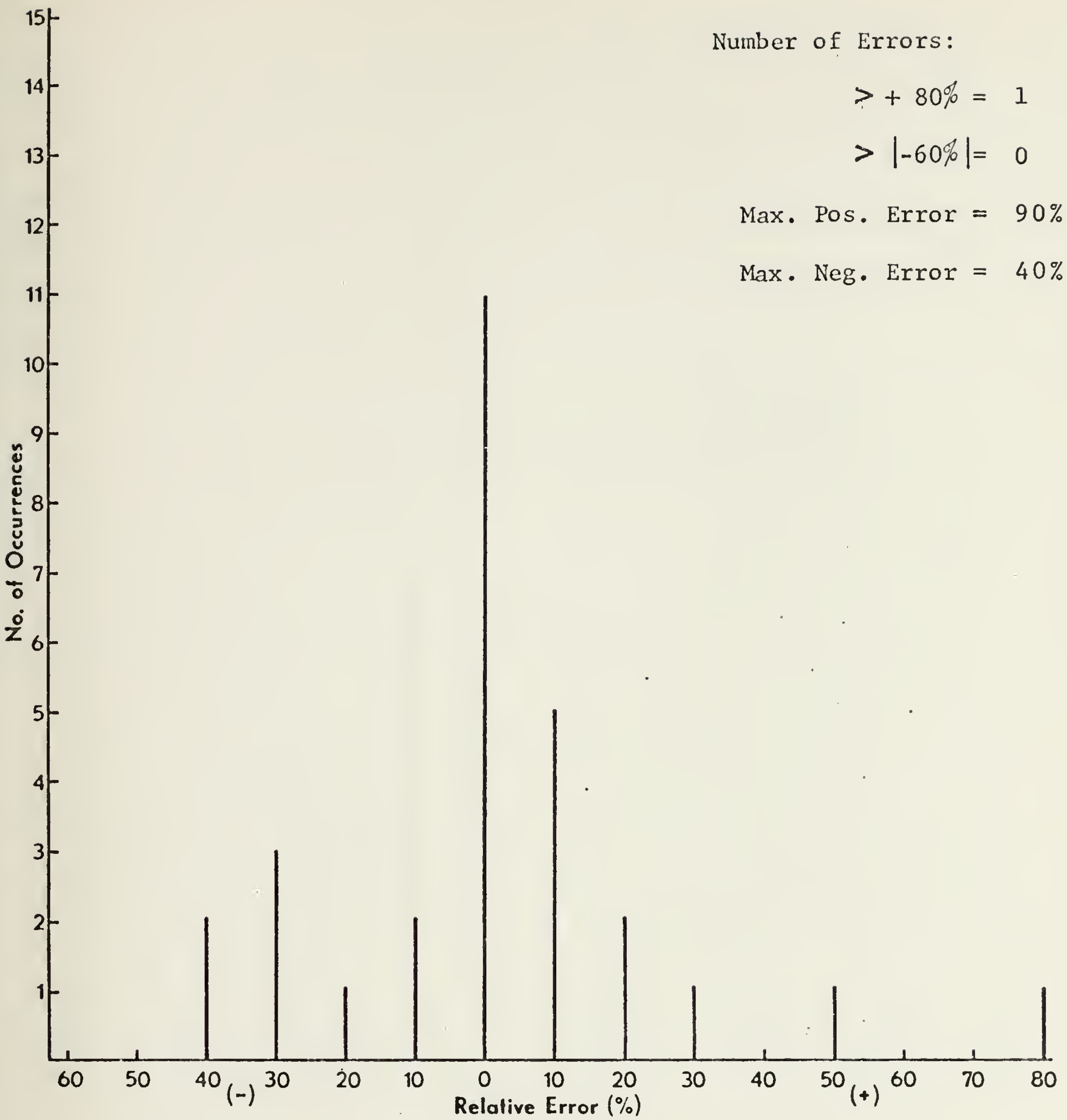

Figure 1. Frequency historgram of 24-hour relative forecast errors for weighted climatology forecast method, dependent test cyclones.

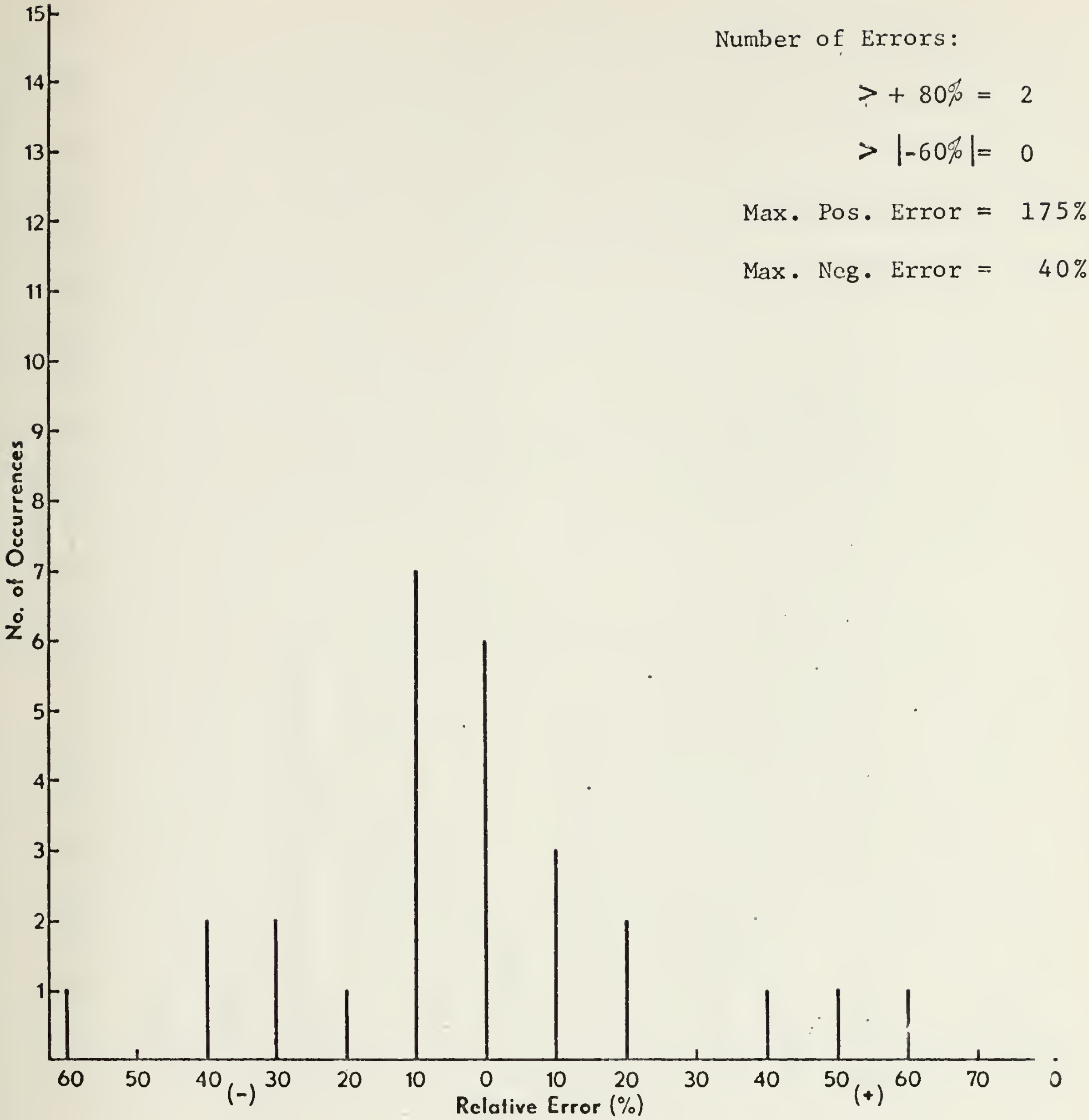

Figure 2. Frequency histogram of 48-hour relative forecast errors for weighted climatology forecast method, dependent test cyclones.

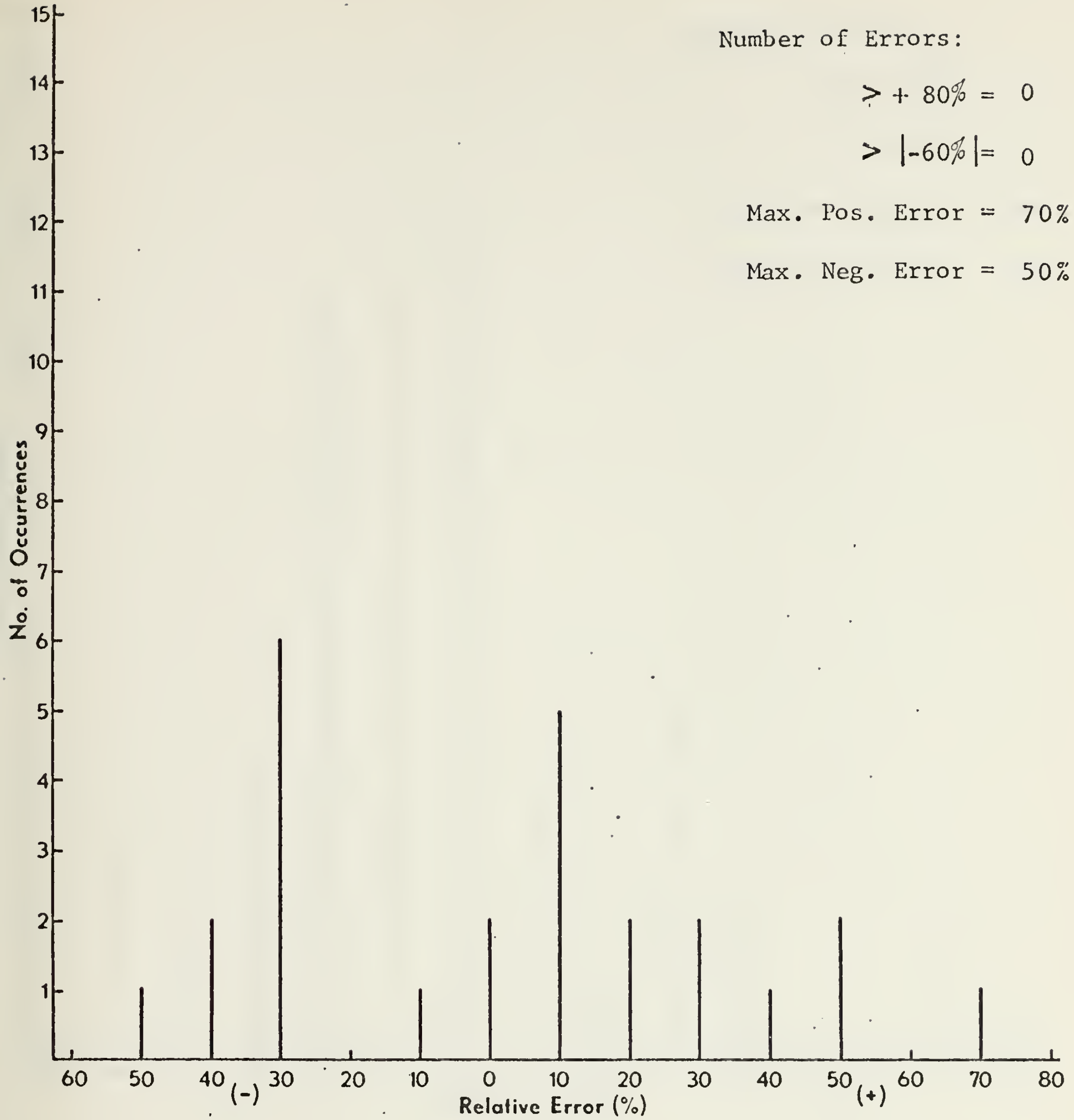

Figure 3. Frequency histogram of 72-hour relative forecast errors for weighted climatology forecast method, dependent test cyclones.

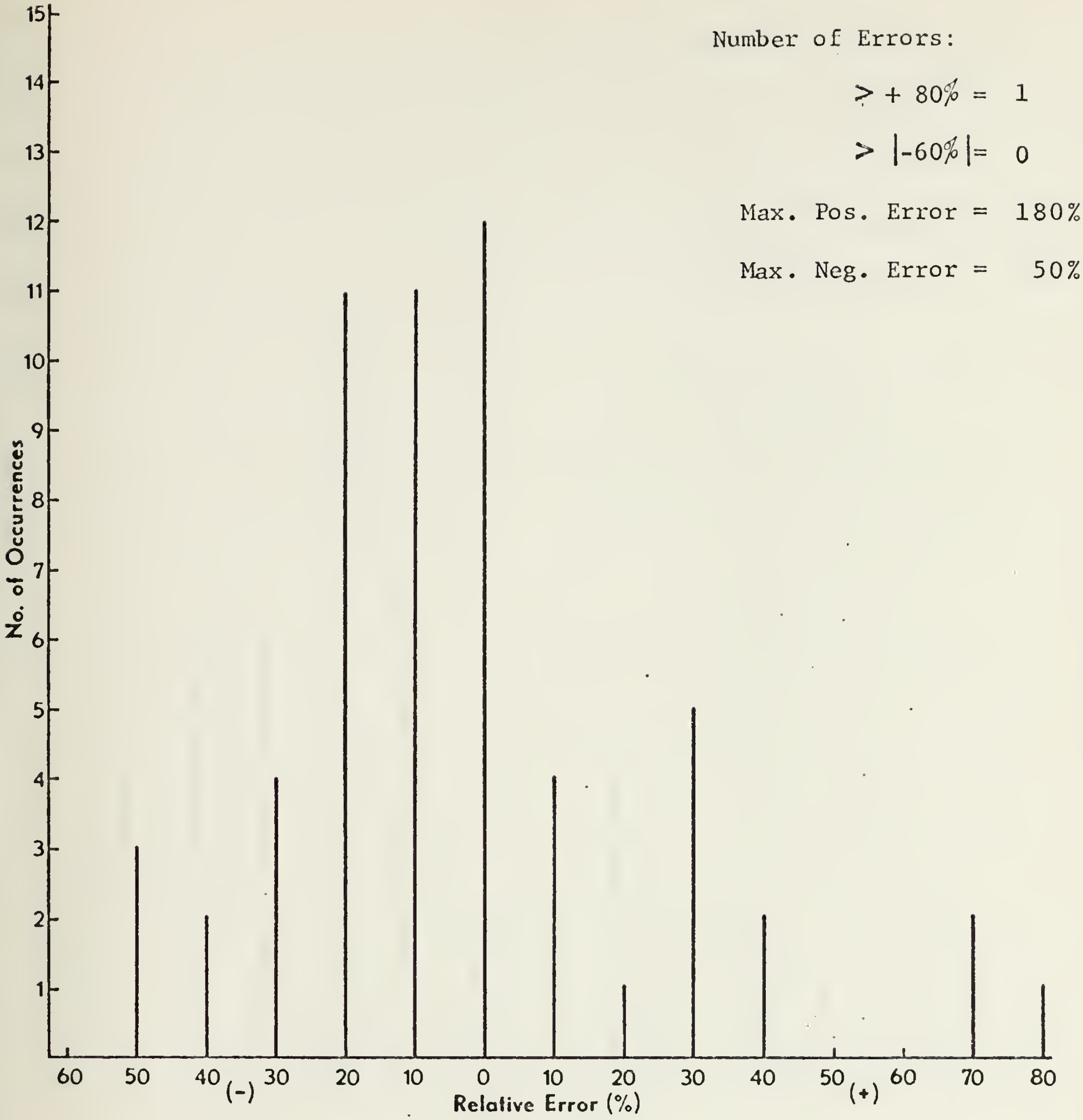

Figure 4. Frequency histogram of 24-hour relative forecast errors for weighted climatology forecast method, independent test cyclones.

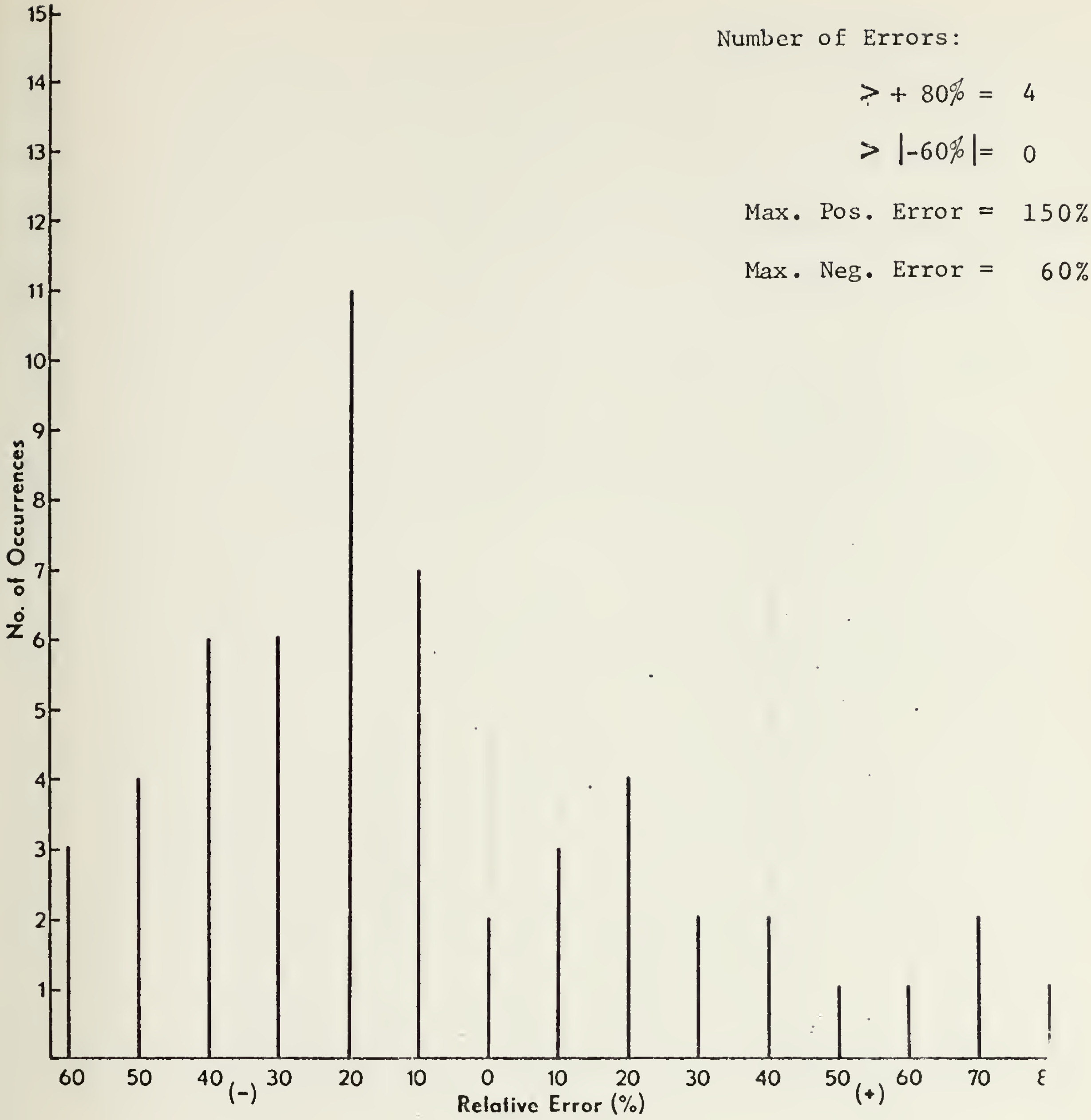

Figure 5. Frequency histogram of 48-hour relative forecast errors for weighted climatology forecast method, independent test cyclones.

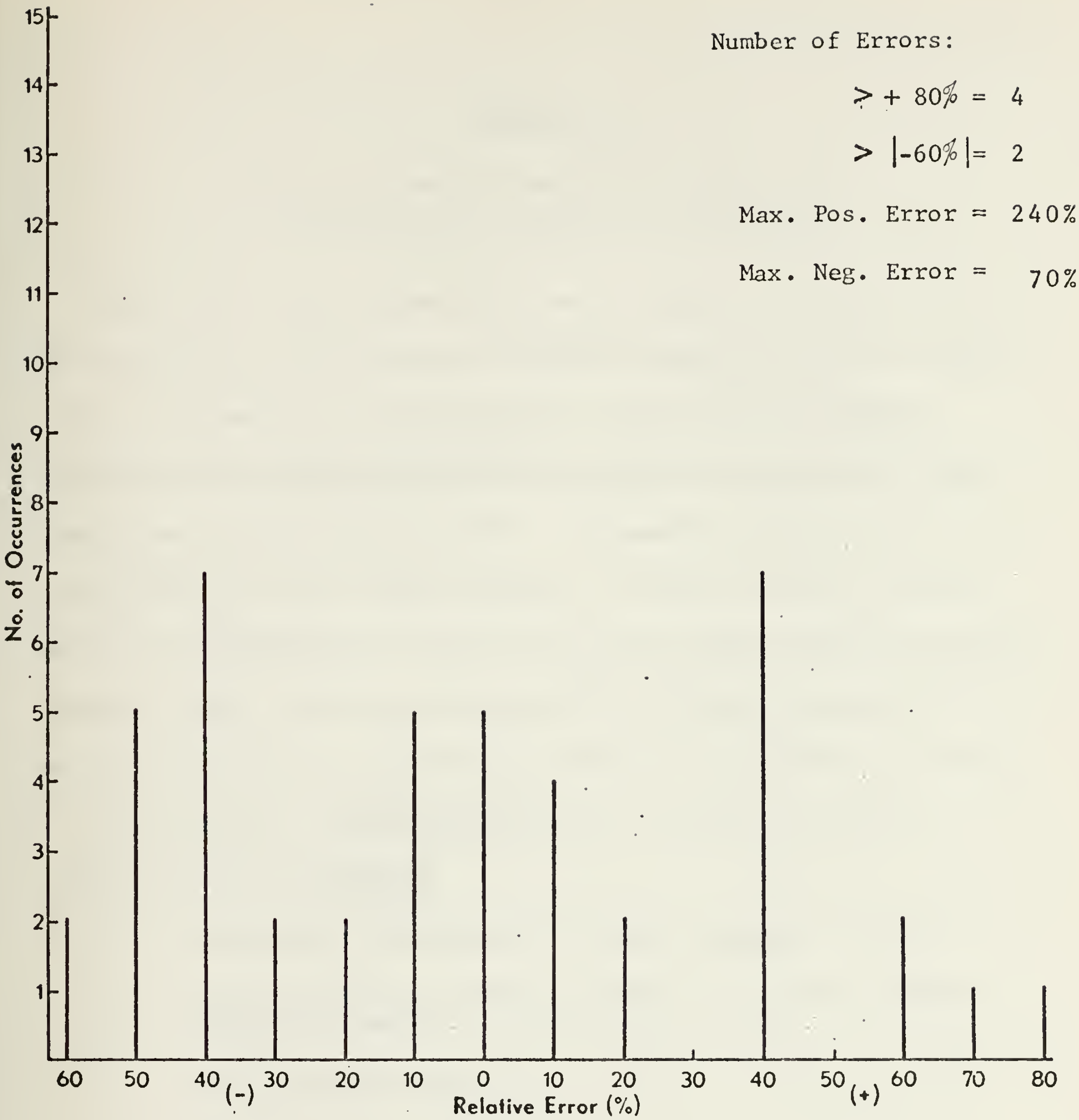

Figure 6. Frequency histogram of 72-hour relative forecast errors for weighted climatology forecast method, independent test cyclones.

APPENDIX A

Original Analog Parameters and Error Estimates of the Analog Elements

The following parameters were compiled at six-hourly intervals for use with the TYFOON analog forecast scheme. Estimated maximum observational errors in the analog elements were provided through informal discussion with Commander J. D. Jarrell, USN. Commander Jarrell is a co-originator of the TYFOON analog forecast scheme and has served as Operations Officer for the Joint Typhoon Warning Center, Guam. Error estimates for the past movement elements are based on estimated errors of six nautical miles in the latitude and longitude of a cyclone position.

<u>Identification Elements</u>

1. Storm name (a number is given unnamed storms)
2. Storm identity number. Month, year and cyclone sequence number
3. Observation number
4. Year
5. Month/Day
6. Hour (GMT)
7. Latitude
8. Longitude

Analog Elements	Estimated Maximum Observational Errors
1. Past 12-hr direction of movement	6 degrees
2. Past 12-hr speed of movement	1 knot
3. Past 18-hr direction of movement	< 6 degrees
4. Past 18-hr speed of movement	< 1 knot
5. Past 24-hr direction of movement	< 6 degrees
6. Past 24-hr speed of movement	< 1 knot
7. Past 48-hr direction of movement	< 6 degrees
8. Past 48-hr direction of movement	< 1 knot
9. Size (average radius of outer closed isobar in whole degrees of latitude)	2 degrees latitude
10. Past 12-hr change of size in degrees latitude	4 degrees latitud
11. Minimum observed sea-level pressure in whole millibars	5 millibars
12. Past 12-hr change in minimum sea-level pressure	10 millibars
13. Maximum wind	10% of the observed value
14. Minimum 700-mb height (above the cyclone)	10 meters
15 Latitude of the 700-mb ridge north of the cyclone	2 degrees latitude
16. 700-mb height at the ridge line north of the cyclone	20 meters

17.	Longitude at 35N of the nearest 700-mb trough west of the cyclone	2 degrees longitude
18.	700-mb height at the intersection of the trough line and 35N	30 meters

APPENDIX B

Dependent Test Cyclones

Dependent test cyclones. The following tropical cyclone reports were selected to examine the forecast potential of the analog elements.

Name	MO-DA-YR	Time (GMT)	Initial Intensity (kt)
Betty	8-06-69	1200	45
Cora	8-17-69	0000	50
Doris	8-02-69	0600	30
Wendy	8-29-68	1800	100
Wendy	8-31-68	0000	140
Shirley	8-17-68	1800	30
Shirley	8-18-68	1200	50
Agnes	8-30-68	0600	45
Agnes	9-01-68	0000	85
Agnes	9-03-68	0600	130
Agnes	9-04-68	0600	145
Agnes	9-05-68	0600	115
Agnes	9-07-68	0600	70
Agnes	9-08-68	0600	60
Polly	8-07-68	1200	40
Polly	8-09-68	0000	55
Polly	8-11-68	0000	50
Polly	8-13-68	0000	55
Louise	8-20-67	0000	30
Louise	8-21-67	0000	55
Marge	8-26-67	1200	100
Opal	9-01-67	0600	75
Opal	9-03-67	1200	155
Opal	9-11-67	1200	90
Rita	8-04-66	1200	60
Rita	8-05-66	1200	75
Carmen	8-10-63	0000	40
Carmen	8-12-63	1800	125
Carmen	8-13-63	0600	110
Carmen	8-14-63	0000	85

APPENDIX C

Acceptance Intervals Defined for the Original Analog Elements

The acceptance intervals defined for the 18 original analog elements are listed below. The range of each interval is defined as plus or minus one-fourth of one standard deviation of the respective element's distribution over the entire data file obtained for the study. This range is centered on the test cyclone element value. If this fraction of the standard deviation resulted in a number less than one, the acceptance interval was defined as $\pm$ 1.0. Intervals vice discrete values were preferred in order to prevent the necessity of identical element values in order for a match to occur. Refer to Appendix A for analog element definition.

Analog Element Number	Acceptance Interval
1	$\pm$ 7.1 degrees
2	$\pm$ 1.4 knots
3	$\pm$ 7.6 degrees
4	$\pm$ 1.3 knots
5	$\pm$ 7.6 degrees
6	$\pm$ 1.2 knots
7	$\pm$ 7.3 degrees
8	$\pm$ 1.0 knots
9	$\pm$ 1.0 degrees latitude
10	$\pm$ 1.0 degrees latitude
11	$\pm$ 5.7 millibars
12	$\pm$ 2.1 millibars
13	$\pm$ 7.9 knots
14	$\pm$ 4.7 dekameters
15	$\pm$ 1.4 degrees latitude
16	$\pm$ 1.0 dekameters
17	$\pm$ 3.5 degrees longitude
18	$\pm$ 1.0 dekameters

APPENDIX D

Indicated Forecast Potentials of the
Original Analog Elements

Indicated forecast potentials of the original analog elements for each forecast period are listed below. The indicated forecast potentials are expressed as a percent of the total number of possible occurrences in which the trend of decreasing degree of matching with increasing forecast error occurred for each element. The results are based on thirty 24-hour forecasts, twenty-nine 48-hour forecasts and twenty-five 72-hour forecasts. Refer to Appendix A for element definitions.

Analog Element Number	Forecast Potential for Given Forecast Periods (%)		
	24-hr	48-hr	72-hr
1	17	29	8
2	41	32	12
3	17	29	12
4	21	18	8
5	25	30	21
6	21	19	21
7	24	29	14
8	12	17	9
9	33	28	32
10	13	28	28
11	23	31	16
12	47	21	24
13	27	38	20
14	33	31	20
15	37	34	12
16	40	38	32
17	33	28	20
18	20	41	36

APPENDIX E

Derived Analog Elements and their Acceptance Intervals

The derived analog elements, formed by various combinations of some of the original analog elements, are listed below together with the acceptance interval that was selected for each. The acceptance interval for each element is centered on the test cyclone value of that element.

Derived Analog Elements	Acceptance Intervals
1. (700-mb ridge height-minimum 700-mb height)	$\pm$ 10 m
2. (700-mb ridge lat-cyclone lat)	$\pm$ 2 deg lat
3. $\frac{\text{700-mb ridge height-minimum 700-mb height}}{\text{700-mb ridge lat-cyclone lat}}$	$\pm$ 10 m/deg lat
4. (700-mb trough height-minimum 700-mb height)	$\pm$ 10 m
5. (700-mb trough long-cyclone long)	$\pm$ 2 deg long
6. $\frac{\text{700-mb trough height-minimum 700-mb height}}{\text{700-mb trough long-cyclone long}}$	$\pm$ 10 m/deg long
7. 1000/700-mb thickness	$\pm$ 2 deg lat
8. Past 24-hr change in derived element #2	$\pm$ 2 deg lat
9. Past 24-hr change in derived element #3	$\pm$ 10 m/deg lat

10.	Past 24-hr change in derived element #5	± 2 deg long
11.	Past 24-hr change in derived element #6	± 10 m/deg long
12.	Past 24-hr change in derived element #7	± 10 m
13.	Past 24-hr change in intensity (maximum wind)	± 10 kt
14.	Past 24-hr change in sea-level pressure	± 5 mb
15.	Past 24-hr change in minimum 700-mb height	± 10 m
16.	Past 24-hr change in 700-mb trough height	± 10 m
17.	Past 24-hr change in 700-mb ridge height	± 10 m
18.	Past 48-hr change in derived element #2	± 2 deg lat
19.	Past 48-hr change in derived element #3	± 10 m/deg lat
20.	Past 48-hr change in derived element #5	± 2 deg long
21.	Past 48-hr change in derived element #6	± 10 m/deg long
22.	Past 48-hr change in derived element #7	± 10 m
23.	Past 48-hr change in intensity (maximum wind)	± 10 kt
24.	Past 48-hr change in sea-level pressure	± 5 mb
25.	Past 48-hr change in minimum 700-mb height	± 10 m
26.	Past 48-hr change in 700-mb trough height	± 10 m
27.	Past 48-hr change in 700-mb ridge height	± 10 m

APPENDIX F

Indicated Forecast Potentials of the Derived Analog Elements

Indicated forecast potentials of the derived analog elements for each forecast period are listed below. The indicated potentials are expressed as a percent of the total number of possible occurrences in which the trend of decreasing degree of matching with increasing forecast error occurred for each element. Refer to Appendix E for element definitions.

Analog Element Number	Forecast Potential for Given Forecast Periods (%)		
	24-hr	48-hr	72-hr
1	27	31	16
2	20	34	20
3	23	34	28
4	20	24	16
5	30	31	20
6	40	34	23
7	27	21	24
8	29	26	25
9	39	41	38
10	21	33	21
11	18	26	17
12	29	22	25
13	46	37	21
14	32	22	21
15	18	37	13
16	29	48	21
17	36	33	21
18	32	17	14
19	36	25	23
20	28	29	18
21	20	17	9
22	36	25	27
23	20	21	18
24	28	33	18
25	8	4	0
26	24	29	23
27	24	29	9

APPENDIX G

Selected Predictors for each Forecast Period

The original and derived analog elements that were selected as predictors for each forecast period are listed below along with their associated weight factors.

24-hr Forecast Period

Predictor	Weight Factor
Past 12-hr change in sea-level pressure	1.42
Past 24-hr change in intensity (maximum wind)	1.39
Past 12-hr speed of movement	1.24
$\dfrac{\text{700-mb trough height-minimum 700-mb height}}{\text{700-mb trough long-cyclone long}}$	1.21
700-mb ridge height	1.21
Past 24-hr change in $\dfrac{\text{700-mb ridge height-minimum 700-mb height}}{\text{700-mb ridge lat-cyclone lat}}$	1.18
700-mb ridge lat	1.12
Past 24-hr change in 700-mb ridge height	1.09
Past 48-hr change in thickness	1.09
Past 48-hr change in $\dfrac{\text{700-mb ridge height-minimum 700-mb height}}{\text{700-mb ridge lat-cyclone lat}}$	1.09
700-mb trough long	1.00
minimum 700-mb height	1.00
size	1.00

48-hr Forecast Period

Predictor	Weight Factor
Past 24-hr change in trough height	1.60
Past 24-hr change in $\dfrac{\text{700-mb ridge height-minimum 700-mb height}}{\text{700-mb ridge lat-cyclone lat}}$	1.37
700-mb trough height	1.37
700-mb ridge height	1.27
current intensity (maximum wind)	1.27
Past 24-hr change in intensity (maximum wind)	1.23
Past 24-hr change in minimum 700-mb height	1.23
700-mb ridge lat	1.13

48-hr Forecast Period (continued)

Predictor	Weight Factor
$\frac{\text{700-mb ridge height-minimum 700-mb height}}{\text{700-mb ridge lat-cyclone lat}}$	1.13
$\frac{\text{700-mb trough height-minimum 700-mb height}}{\text{700-mb trough long-cyclone long}}$	1.13
Past 24-hr change in 700-mb trough long-cyclone long	1.10
Past 24-hr change in 700-mb ridge height	1.10
Past 48-hr change in sea-level pressure	1.10
Past 12-hr change in speed of movement	1.07
Past 24-hr change in direction of movement	1.00

72-hr Forecast Period

Predictor	Weight Factor
Past 24-hr change in $\frac{\text{700-mb ridge height-minimum 700-mb height}}{\text{700-mb ridge lat-cyclone lat}}$	1.81
700-mb trough height	1.71
700-mb ridge lat	1.52
Size	1.52
Past 12-hr change in size	1.33
$\frac{\text{700-mb ridge height-minimum 700-mb height}}{\text{700-mb ridge lat-cyclone lat}}$	1.33
Past 48-hr change in thickness	1.29
Past 24-hr change in thickness	1.19
Past 12-hr change in sea-level pressure	1.14
Past 24-hr speed of movement	1.00

APPENDIX H

Independent Test Cyclones

Independent test cyclones. The following tropical cyclone reports were selected as independent test cases for the analog forecast program.

Name	MO-DA-YR	Time (GMT)	Initial Intensity (kt)
Cora	8-18-69	1200	65
Cora	8-20-69	0600	80
Polly	8-04-68	0600	55
Trix	8-24-68	0600	35
Trix	8-25-68	1200	40
Trix	8-26-68	0600	50
Bess	9-01-68	0000	40
Bess	9-03-68	0600	50
Wendy	9-02-68	0000	105
Wendy	9-04-68	0000	85
Wendy	9-06-68	0600	60
Hope	8-05-67	0600	45
Hope	8-06-67	0000	55
Marge	8-24-67	0600	30
Marge	8-25-67	0000	40
Opal	9-05-67	0600	110
Opal	9-06-67	0600	115
Opal	9-07-67	0600	95
Rita	8-02-66	1200	25
Rita	8-03-66	1200	35
Rita	8-06-66	0600	50
Alice	8-27-66	0000	55
Alice	8-29-66	1800	75
Alice	8-31-66	1800	100
Alice	9-01-66	1200	130
Alice	9-02-66	1200	130
Tess	8-12-66	1200	25
Tess	8-13-66	1200	35
Tess	8-14-66	1800	55
Cora	8-31-66	0600	50
Cora	9-01-66	1200	100
Cora	9-02-66	1800	130
Cora	9-04-66	0000	130
Cora	9-05-66	0600	140
Kim	8-04-65	0600	25
Kim	8-05-65	0600	50
Kim	8-06-65	0600	60

Name	MO-DA-YR	Time (GMT)	Initial Intensity (kt)
Lucy	8-16-65	0000	85
Lucy	8-17-65	0000	120
Lucy	8-19-65	0000	120
Lucy	8-20-65	0600	150
Lucy	8-21-65	0600	120
Olive	8-29-65	0000	150
Olive	8-30-65	0000	130
Olive	8-30-65	1800	110
Kathy	8-12-64	0600	35
Kathy	8-13-64	0600	80
Kathy	8-14-64	1200	80
Kathy	8-15-64	1800	60
Kathy	8-17-64	0000	75
Kathy	8-18-64	0600	110
Kathy	8-19-64	1200	110
Kathy	8-20-64	1800	100
Kathy	8-22-64	0000	85
Marie	8-15-64	0600	30
Marie	8-15-64	1800	30
Marie	8-16-64	0600	30
Sally	9-04-64	0000	55
Sally	9-05-64	0000	85
Sally	9-06-64	0600	130
Sally	9-07-64	1800	160

REFERENCES

1. Garstang, M., 1972: A review of hurricane and tropical meteorology. Bulletin of the American Meteorological Society, 53, 612-630.

2. Fleet Weather Central/Joint Typhoon Warning Center, 1971: Annual Typhoon Report-1971. COMNAVMARIANAS, Guam, 315 pp.

3. Fleet Weather Central/Joint Typhoon Warning Center, 1970: Annual Typhoon Report-1970. COMNAVMARIANAS, Guam, 190 pp.

4. Jarrell, J. D., and Somervell, W. L., 1970: A computer technique for using typhoon analogs as a forecast aid. Technical paper 6-70, Navy Weather Research Facility, Norfolk, Va. 46 pp.

5. Atkinson, G. D., 1971: Forecasters' guide to tropical meteorology. Technical report 240, Air Weather Service (MAC), U.S. Air Force, April, 360 pp.

6. Jarrell, J. D., 1971: JTWC research presentation, Proceedings Report, 1971 Tropical Cyclone Conference, Tokyo, Japan, February, 95 pp.

7. Brand, S., 1972: Geographic and monthly variation of rapid intensification and low-latitude weakening of tropical cyclones of the western North Pacific Ocean, Technical paper 5-72, Environmental Prediction Research Facility, 28 pp.

8. Liechty, K. R., 1972: Intensity changes of tropical cyclones in the western North Pacific Ocean during 1960-1969, M.S. thesis, Naval Postgraduate School, Monterey, September, 136 pp.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Professor R. J. Renard Code 51Rd Department of Meteorology Naval Postgraduate School Monterey, California 93940	10
4.	Lieutenant Kent W. Foster USN 409 Robineau Road Syracuse, New York 13207	6
5.	Professor R. L. Elsberry, Code 51Es Department of Meteorology Naval Postgraduate School Monterey, California 93940	1
6.	Department of Meteorology Naval Postgraduate School Monterey, California 93940	2
7.	Naval Weather Service Command Naval Weather Service Headquarters Washington Navy Yard Washington, D. C. 20390	1
8.	Commanding Officer Fleet Numerical Weather Central Naval Postgraduate School Monterey, California 93940	1
9.	Commanding Officer Fleet Weather Central/Joint Typhoon Warning Center COMNAVMARIANAS, Box 2 FPO San Francisco, California 96610	1
10.	Commanding Officer Fleet Weather Central, Pearl Harbor Box 113 FPO San Francisco, California 96610	1

11. Commanding Officer — 1
Fleet Weather Central
Norfolk Naval Air Station
Norfolk, Virginia 23511

12. Commanding Officer — 1
Environmental Prediction Research Facility
Monterey, California 93940

13. Commanding Officer — 1
Fleet Weather Facility
Naval Air Station
Alameda, California 94501

14. Commander Jerry D. Jarrell — 1
Department of Meteorology
Naval Postgraduate School
Monterey, California 93940

15. Mr. Samson Brand — 1
Environmental Prediction Research Facility
Monterey, California 93940

16. Library — 1
Environmental Prediction Research Facility
Monterey, California 93940

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

NATING ACTIVITY (Corporate author)

val Postgraduate School
nterey, California 93940

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

RT TITLE

velopment and Application of an Analog Scheme for Predicting e Intensification of Western North Pacific Tropical Cyclones

RIPTIVE NOTES (Type of report and, inclusive dates)

ster's Thesis; March 1973

OR(S) (First name, middle initial, last name)

nt W. Foster

RT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
rch 1973	97	8

TRACT OR GRANT NO.

JECT NO.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

RIBUTION STATEMENT

Approved for public release; distribution unlimited.

PLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Naval Postgraduate School
Monterey, California 93940

RACT

Various meteorological parameters were examined to determine their predictive value for forecasting intensity changes of Western North Pacific tropical cyclones using an analog forecast scheme. A number of procedures were devised to quantitatively define the forecast potentials of these parameters in a systematic method. Based on the results of these procedures, predictors for the 24-hour, 48-hour, and 72-hour forecast periods were defined.

To evaluate the skill of the predictors and the procedures used to define them, an analog intensification forecast scheme was developed and applied to a number of test cyclones. The results of these forecasts were compared to the acceptability criteria established by the Joint Typhoon Warning Center, Guam and to official forecasts issued by this activity.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Tropical cyclone						
Analog forecast						
Statistical forecast						
North Pacific Ocean						
Western North Pacific Ocean						
Forecasting						
Typhoon						
Intensity Forecasting						

Thesis 143419
F658 Foster
c.1 Development and application of an analog scheme for predicting the intensification of Western North Pacific tropical cyclones.